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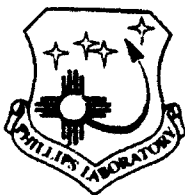
# EFFECTS OF ENERGETIC PARTICLE EVENTS ON VLF/LF PROPAGATION PARAMETERS/1989

W. I. Klemetti  
J. E. Rasmussen  
P. A. Kossey

4 December 1992

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13. ABSTRACT (Maximum 200 words)  This report is a summary of disturbance effects of three major energetic particle events (PCA's) on VLF/LF propagation parameters as observed by the Phillips Laboratory High Resolution Oblique VLF/LF Ionosounder located in northern Greenland. Disturbance effects on ionospheric reflectivity parameters, including deduced reflection heights and plane wave reflection coefficients, are presented along with riometer, magnetometer, and satellite particle detector data.				
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## Preface

The authors thank Mr. Jens C. Ostergaard of the University of Lowell and Mr. John P. Turtle of Rome Laboratory for their assistance in data interpretation and presentation. Also, we thank Svend Erik Ascanius of the Danish Meteorological Institute (DMI) for the operation of the instrumentation at the field data collection station in Qanaq, Greenland.

Appreciation is also extended to the Danish Commission for Scientific Research in Greenland for making these measurements possible, and to Mr. Jorgen Taagholt and Mr. V. Neble Jensen of the Danish Meteorological Institute's Ionospheric Laboratory for their cooperation on this program.

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## Effects of Energetic Particle Events on VLF/LF Propagation Parameters / 1989

### 1. INTRODUCTION

This report covers three major energetic particle events that occurred during the late summer and fall of 1989. The data presented in this report show the effects of these events on VLF/LF propagation parameters. The propagation data were obtained by the Phillips Laboratory High Resolution VLF/LF Ionosounder located in Northern Greenland.<sup>1,2</sup> The ionosounder provides data from which effective ionospheric reflection heights and plane wave reflection coefficients  $_{||}R_{||}$  and  $_{||}R_{\perp}$  can be determined.<sup>3</sup> Also included are data on particle flux density, HF ionometer absorption and geomagnetic field intensity.

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Received for publication 1 Dec 1992

1. Lewis, E.A. et al (1973) Measurements Of Ionospheric Reflectivity from 6 to 35 kHz, *J. Geophys. Res.* 78:19.
2. Kossey, P.A. et al (1974) *VLF Pulse Ionosounder Measurements of Reflection Properties of the Lower Ionosphere*, Akademie Verlag, COSPAR, July.
3. Budden, K.G. (1961) *Radio Waves in the Ionosphere*, Cambridge University Press, London, p85.

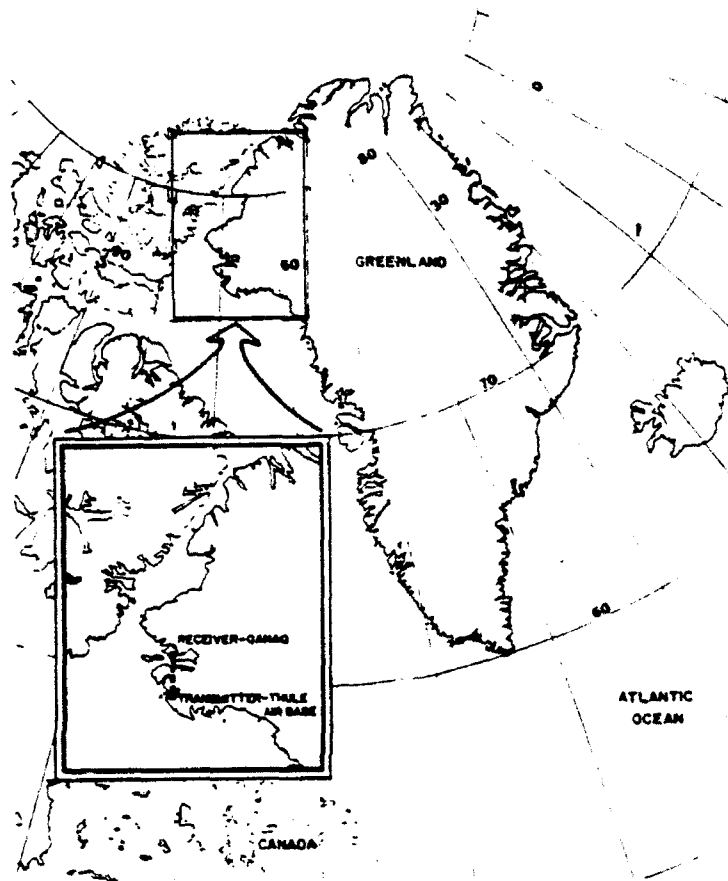


Figure 1. Ionosounder Propagation Path  
Thule AB - Qanaq, Greenland

The VLF/LF ionosounding transmitter (Figure 1) was located at Thule Air Base Greenland ( $76^{\circ} 33' \text{ N Lat.}$ ,  $68^{\circ} 40' \text{ W Long.}$ ), and the receiving site was 106 km north at the Danish Meteorological Institute's Ionospheric Observatory in Qanaq, Greenland ( $77^{\circ} 24' \text{ N Lat.}$ ,  $69^{\circ} 20' \text{ W Long.}$ , Geomagnetic Lat.  $89^{\circ} 06' \text{ N}$ ). The ionosounding transmissions consist of a series of extremely short (approximately  $100 \mu \text{ sec}$ ) VLF pulses, precisely controlled in time, and radiated from a 130 meter vertical antenna (Figure 2a). Orthogonal loop antennas (Figure 2b) are used to receive the two polarization components of the ionospherically reflected skywave signal. One loop, oriented in the plane of propagation, senses the groundwave and the unconverted or "parallel" (II) component of the down-coming skywave; the second loop, nulled on the groundwave, senses the converted or "perpendicular"

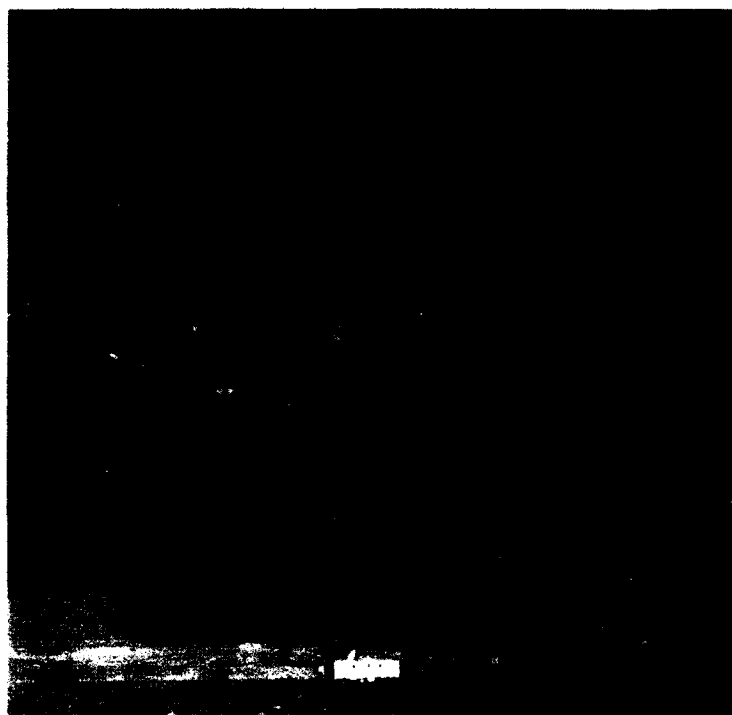


Figure 2a. Transmitting Antenna - Thule AB, Greenland



Figure 2b. Orthogonal Receiving Antennas - Qanaq, Greenland



skywave component. The signals from the antennas are digitally averaged to improve the signal-to-noise ratio of the individual received waveforms before they are recorded on magnetic tape. At the receiver, the radiated signal arrives first by groundwave propagation (Figure 3). Due to the extremely short pulse length, this signal passes the receiver before the arrival of the ionospherically reflected skywave pulse, providing independent groundwave and skywave data. An example of the observed waveforms is presented in Figure 4, where the parallel waveform (a) consists of a groundwave propagated pulse followed by a quiet interval (containing some low level off-path groundwave reflections) and then the first-hop parallel skywave component. The perpendicular skywave component (b) is also shown. Each of these waveforms is comprised of 256 digitally averaged points, spaced  $2\mu$  sec apart. Ionospheric reflection parameters are derived by computer processing of the ground and ionospherically reflected waveforms, with allowances made for factors such as ground conductivity and antenna patterns (see Section 2.2).

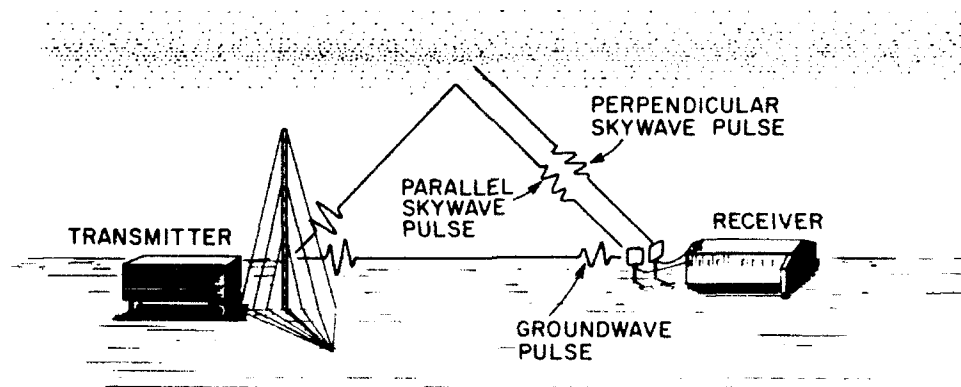


Figure 3. Basic Ionosounding Experiment

Figure 5 shows the Fourier Amplitude spectrum of the received groundwave signal. Although the data presented are generally limited to frequencies in the first or principal lobe of the spectrum, information at higher frequencies can be used when sufficient signal-to-noise conditions exist. There is, however, a frequency range around each spectral null where insufficient signal exists for valid measurements.

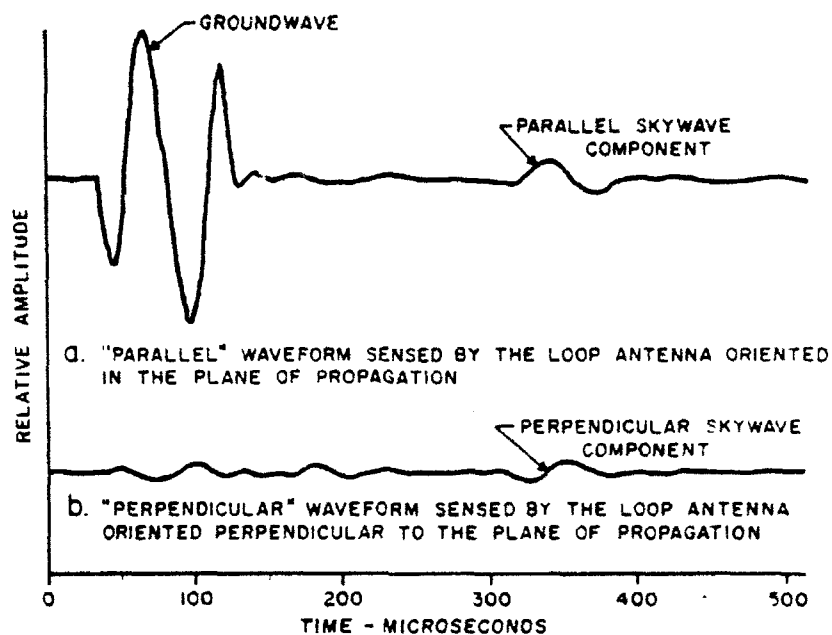
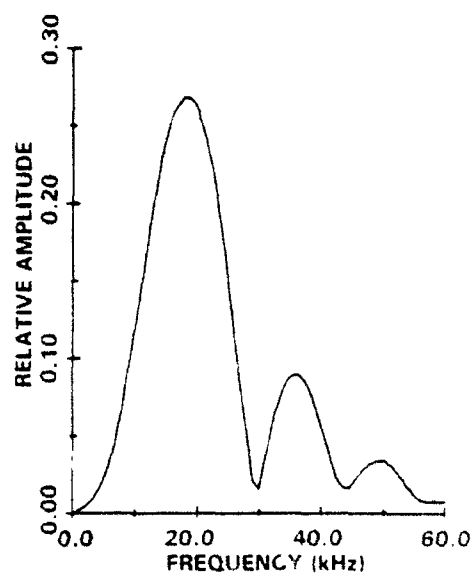


Figure 4. Example of Parallel and Perpendicular Waveforms

Figure 5. Fourier Amplitude Spectrum of Transmitted Pulses.



## 2. EVENT DATA

The data are presented for each disturbance in three general formats; (1) a synthetic three-dimensional display beginning approximately two days prior to the onset of the event and covering a 14 day period; (2) in the frequency domain with deduced reflection heights and plane-wave reflection coefficients plotted as a function of frequency over the range from approximately 5 to 30 kHz; and (3) Deduced reflection heights and plane-wave reflection coefficients presented as functions of time-of-day over a two-week period. In addition to reflection information, this section contains data on geomagnetic field activity, ionospheric absorption and solar proton fluxes.

### 2.1 Observed Waveforms

A synthetic three-dimensional waveform display is presented for a 2-week period containing each disturbance event, together with a display of a comparable 2-week period from a year when there was no disturbance during the period. For each display the waveforms were stacked one behind the other linear in time, progressing from bottom to top. Each individual waveform is a one hour average of approximately 1.4 million pulses. The horizontal scale for these plots is linear in time (microseconds), measured from the beginning of the groundwave. This scale can be used to calculate an effective height of reflection by attributing the time delay between the start of the groundwave and the start of the skywave to the difference in travel time, assuming a sharply bounded, mirror-like ionosphere. Figure 6 shows a conversion curve for this based on simple geometry and the specific Thule AB-Qanaq, Greenland separation of 106 km. For the disturbance periods, fixed local clutter, amounting to about 2 percent of the groundwave amplitude, was removed to avoid interference with the skywave and improve the appearance of the plotted waveforms.

The three-dimensional displays of the disturbed parallel waveforms are given for each of the three events in Parts A and B of Figures 7 through 9. A plot of the diurnal variation in solar zenith angle for the midpoint of the path appears in Part C. The perpendicular waveform displays are shown in Parts D and E. The time of maximum particle flux is indicated on the disturbance plots. This data was not as comprehensive as our previous data, as the system was operating on a time sharing basis with another experiment. The operational cycle was 2 hours on and 2 hours off, thus creating a 2 hour gap in the data every 2 hours.

### 2.2 Quantitative Reflection Parameters

For each event individual parallel and perpendicular waveforms were selected in order to show the effects of the disturbance on the ionospheric reflection heights and reflection coefficients as a function of frequency. The selected waveforms from the disturbance period are shown in Part F of the data figures, whereas the corresponding waveforms from the undisturbed period are shown in Part G.

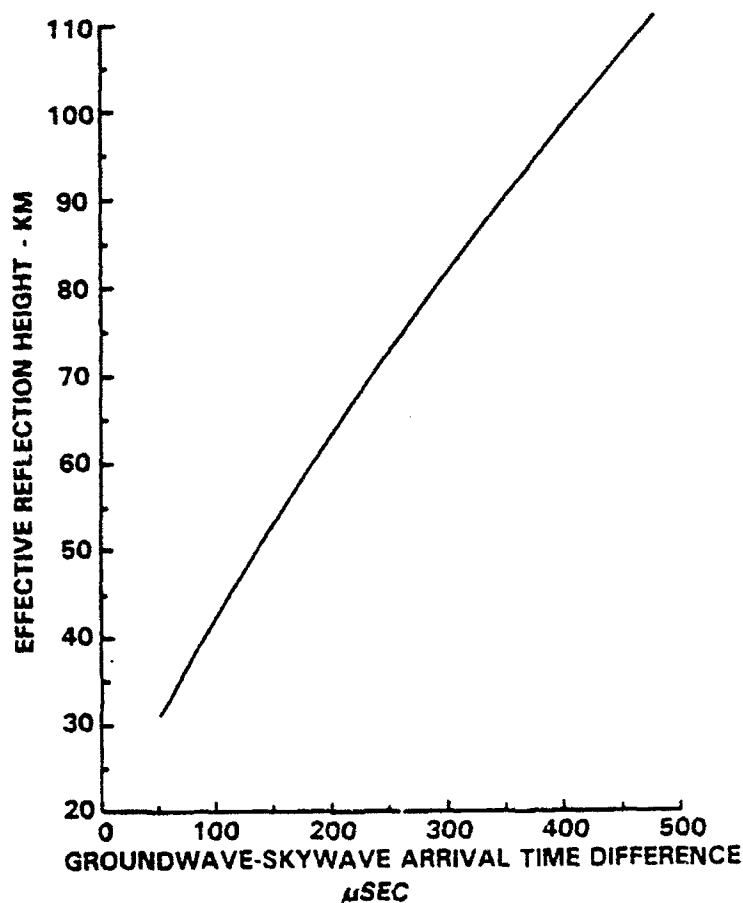


Figure 6. Conversion Curve Groundwave-Skywave Arrival Time Difference to Reflection Height

#### 2.2.1 REFLECTION HEIGHTS DETERMINED FROM GROUP DELAY DATA

Group mirror heights (GMH) of reflection were obtained by determining the group delay of the skywave relative to the groundwave and attributing this difference to the difference in the propagation distances. The group delay can be defined as the rate of change of the phase with frequency as discussed in Lewis et al.<sup>1</sup> For the GMH data presented in this report, a finite frequency difference of 1.0 kHz was used, and the corresponding phase difference as a function of frequency for the groundwave and both skywave signals was obtained by Fourier analysis of the respective pulses. The GMH calculations took into account ground conductivity ( $10^{-3}$  mhos/m is assumed), with the Wait and Howe<sup>4</sup> corrections applied. Group mirror heights for the parallel and perpendicular waveforms are plotted as a

4. Wait, J.R. and Howe, H.H. (1956), *Amplitude and Phase Curves for Groundwave Propagation in the Band 200 Cycles per Second to 500 Kilocycles*, National Bureau of Standards, U.S. Circ. No. 574.

function of frequency in Parts H and I of Figures 7 through 9 for both normal and disturbed conditions. The GMH's are also presented as a function of time-of-day for the average frequency of 16.5 kHz. In Figures 7 through 9, (Parts J and K) parallel and perpendicular reflection height information is given based on one-hour averaged data for the two-week period. Also plotted is a line showing a 14-day average of group heights recorded during a time of normal solar activity. Parts L and M show the 24-hour period of event onset in greater detail based on data that has been averaged in 15 minute time blocks. Parts L and M include an undisturbed reflection height curve for reference purposes. The reference curve is a series of points created by averaging an undisturbed 14-day period in one hour blocks.

### 2.2.2 EFFECTIVE PLANE-WAVE REFLECTION COEFFICIENTS

Assuming the ionosphere acts as a "mirror" at the GMH, plane-wave reflection coefficients were obtained by comparing the ratio of the skywave Fourier amplitude at a specific frequency to that of the groundwave, taking into account the wave spreading, earth curvature, ground conductivity, path lengths and antenna patterns (including ground image effects).

The reflection coefficients  $R_{\parallel}$ , obtained from the analysis of the parallel skywave component, are plotted as a function of frequency for both normal and disturbed conditions in Part H. From the corresponding perpendicular skywave pulses, the coefficient  $R_{\perp}$  was obtained; it appears as a function of frequency in Part I. The  $R_{\parallel}$  coefficient for 16 kHz is plotted as a function of time-of-day in Part N along with the averaged normal coefficient. As with the reflection heights, a more detailed  $R_{\parallel}$  coefficient plot, based on 15-min averaged data is shown in Part L. To show the variation in reflectivity as a function of frequency during the event, the reflection coefficients were calculated at 8 kHz, 16 kHz, and 22 kHz and are plotted in Part O as a function of time for the 14-day period. The corresponding reflection coefficient plots for  $R_{\perp}$  are given in Parts P, Q, and M.

For certain coefficient data points, plotted as asterisks, the reflection coefficient appears without a corresponding GMH. For these particular data, only the skywave-groundwave ratios could be obtained since the skywave signals were too weak to provide reliable group delay information. The reflection coefficients were estimated, using a nominal GMH of 80 km in the calculations. These estimated coefficient values are included in the averages presented in Parts N, O, P, and Q, but the assumed heights are not used in the GMH averages.

### 3. SUPPLEMENTARY DATA

To more fully interpret the effects of ionospheric disturbances on the LF/VLF ionosounding data, information from several geophysical sensors are included. Parts R and S of Figures 7 through 9 present data from a 30 MHz riometer and a magnetometer operated by RADC at Thule AB, Greenland. The riometer, the conventional monitor of ionospheric disturbances, measures the signal level of

cosmic noise passing through the ionosphere. Increased absorption caused by enhanced D-region ionization from energetic particles causes a decrease in the received noise level. The output from the riometer during undisturbed conditions shows a diurnal (quiet day) variation. In this report the diurnal variation has been subtracted from the data leaving only the absorption changes resulting from precipitation of energetic particles into the D-region. The data plotted in Part R of each figure give riometer absorption levels, a zero level representing undisturbed conditions, and absorption in dB is plotted on a vertical logarithmic scale. The effects of energetic particle events are seen as an abrupt increase in the absorption level followed by a gradual recovery to normal levels over a period of several days. Diurnal variations in the level of absorption are caused by variations in the amount of solar illumination on the ionosphere. The magnetometer data (Part S) plotted are the X component of the polar magnetic field determined by a 3-axis fluxgate magnetometer at Thule AB, Greenland. The magnetometer responds to the effects of the polar ionospheric current systems related to disturbance events.

In addition to the information from the ground-based monitors, particle flux data obtained from the GOES-7 geosynchronous satellite operated by the National Oceanic and Atmospheric Administration are presented.\* The data presented in Part T are 5 minute averages of differential flux levels for protons in two energy ranges: 4.2 to 8.7 MeV and 15.0 to 44.0 MeV. These particle data are important for relating the VLF/LF ionosounder effects to the size of a particle disturbance. Table 1 contains a listing of events we recorded during our operations in the years 1974 thru 1979 along with these events occurring in 1989. The maximum proton flux levels for the 1989 PCA events were from an energy range of 15.0 to 44.0 MeV, while those associated with the earlier events were for a range from 13.7 to 25.2 MeV.

#### 4. DISTURBANCE CHARACTERISTICS

Table 1 presents a summary of the data for the three events covered in this report. In addition, data are included for 30 previous events covered in a series of previous reports.<sup>5,6,7</sup> As shown in Table 1, the August, September and October

\* Particle data obtained from the National Geophysical Data Center, Boulder, CO

5. Turtle, J.P., Rasmussen, J.E., Klemetti, W.I. (1980), *Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1974-1977*, RADC-TR-80-308, ADA104508.

6. Turtle, J.P., Rasmussen, J.E., Klemetti, W.I. (1981), *Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1978*, RADC-TR-81-82, ADA103945.

7. Turtle, J.P., Rasmussen, J.E., Klemetti, W.I. (1982), *Effects of Energetic Particle Events on VLF/LF Propagation Parameters, 1979*, RADC-TR-82-79, ADA118790.

PCA events of 1989 caused a decrease in reflection heights to as low a level as we had seen since we began collecting data in 1974. The characteristics of the effects of energetic particles on the VLF/LF propagation parameters are a function of the event size and the solar illumination conditions at the time of the event. The decrease in reflection heights of both the parallel and perpendicular components is coincident with the influx of energetic particles. The final level of the reflection height depends upon the magnitude of the particle flux and the solar illumination conditions during the event.

The 12 August (day of year 224) event is a daytime event as the solar zenith angle never exceeds 90 degrees. This event appears typical of previous day events in that the reflection height drops rapidly and slowly recovers. The reflection height during the event also displays no discernible diurnal variations. Characteristic of daytime events, the magnitudes of the disturbed ( $\perp$ ) reflection coefficients show a marked increase with respect to the undisturbed conditions.

The 29 September (day of year 272) event is a typical day-night event, with the solar zenith angle ranging from 79 degrees to 106 degrees. As seen previously during this type of event, the disturbance pattern is more complex with an enhancement of the daytime reflection coefficients and a drop in the nighttime coefficients. These conditions slowly return to normal as the ionosphere recovers.

The 19 October (day of year 292) event is a day-night event, although the solar zenith angle never was less than 86 degrees or 4 degrees above the horizon on the 19 of October. The 3D plots prior to the onset of this event show very little diurnal variation. The reflection heights during the event show the typical rapid drop and gradual recovery, with a more pronounced diurnal variation than noted prior to the event.

Table 1. Solar Particle Data

Event Date		Minimum 16 kHz Parallel Reflection Heights (km)	30 MHz Riometer Absorption (dB)	Illumination Conditions
1989 Events				
12 Aug	(224)	52	11	daytime
29 Sep	(272)	51	10	day-night
19 Oct	(292)	50	>15	day-night
1979 Events				
2 Mar	(061)	63	<0.5	day-night
3 Apr	(093)	61	2	day-night
6 Jun	(157)	58	6	daytime
1 Aug	(213)	70	<0.5	daytime
19 Aug	(231)	57	4	daytime
8 Sep	(251)	63	0.5	daytime
15 Sep	(258)	58	2	day-night
16 Nov	(320)	62	1	day-night
1978 Events				
13 Feb	(044)	56	6	day-night
25 Feb	(056)	64	<0.5	day-night
7 Mar	(066)	70	<0.5	day-night
8 Apr	(098)	65	<0.5	day-night
11 Apr	(101)	58	3	daytime
17 Apr	(107)	60	0.5	daytime
7 May	(127)	57	1	daytime
11 May	(131)	63	<0.5	daytime
31 May	(151)	63	1	daytime
11 Jul	(192)	64	1	daytime
8 Sep	(251)	63	<0.5	day-night
23 Sep	(266)	51	10	day-night
8 Oct	(281)	65	<0.5	day-night
10 Nov	(314)	65	1	day-night
12 Dec	(345)	74	<0.5	nighttime
1974-1977 Events				
5 Nov 74	(309)	63	<0.5	day-night
30 Apr 76	(121)	53	3	daytime
22 Aug 76	(235)	60	1.7	daytime
26 Jul 77	(207)	70	<0.5	daytime
24 Sep 77	(267)	57	2	day-night
22 Nov 77	(326)	64	0.75	nighttime



## 12 August 1989 (DAY 224) Solar Proton Event

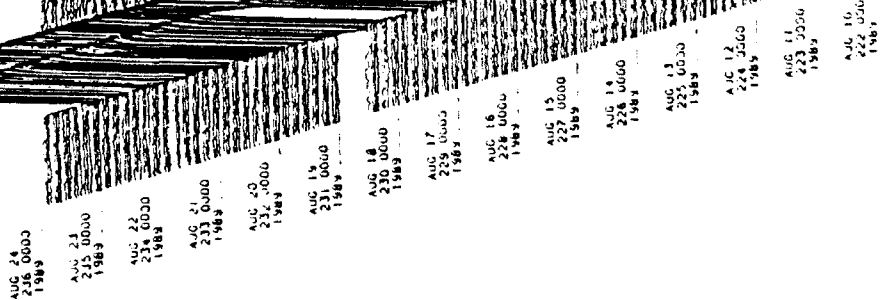
DAY:	224 (12 August 1989)
Report Figure:	7
Related Solar Flare:	1100 UT 12 Aug 1989 X-ray class: X2.6
Start of Ionospheric Disturbance:	1400 UT 12 Aug 1989
Time of Maximum 15.0-44.0 MeV Proton Flux:	0500 UT 13 Aug 1989
Maximum Flux:	70 particles/cm sec sr MeV
Length of Particle Event:	8 days
Lowest 16 KHz Reflection Height:	52 km
30 MHz Riometer Absorption:	> 11 dB
Solar Zenith Angle Range:	62deg - 88deg
Illumination Conditions:	Day

A strong event occurring during full daylight conditions lowering the ionospheric reflection heights from 83 km at 1200 UT on Day 223 (11 Aug) to a low reading of 52 km at the corresponding time on Day 225, the second day after the onset. The normal ( $R_{11}$ ) reflection coefficients increased in amplitude typical of data recorded during previous events under full daylight conditions. The corresponding converted ( $R_{\perp}$ ) coefficients decreased in accordance with waves reflecting at lower altitudes where the collision forces are larger.

# RECEIVED PARALLEL WAVEFORMS

## A. DISTURBED CONDITIONS

AUG 1989



## B. NORMAL CONDITIONS

AUG 1987

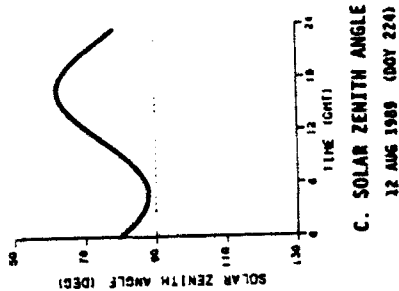
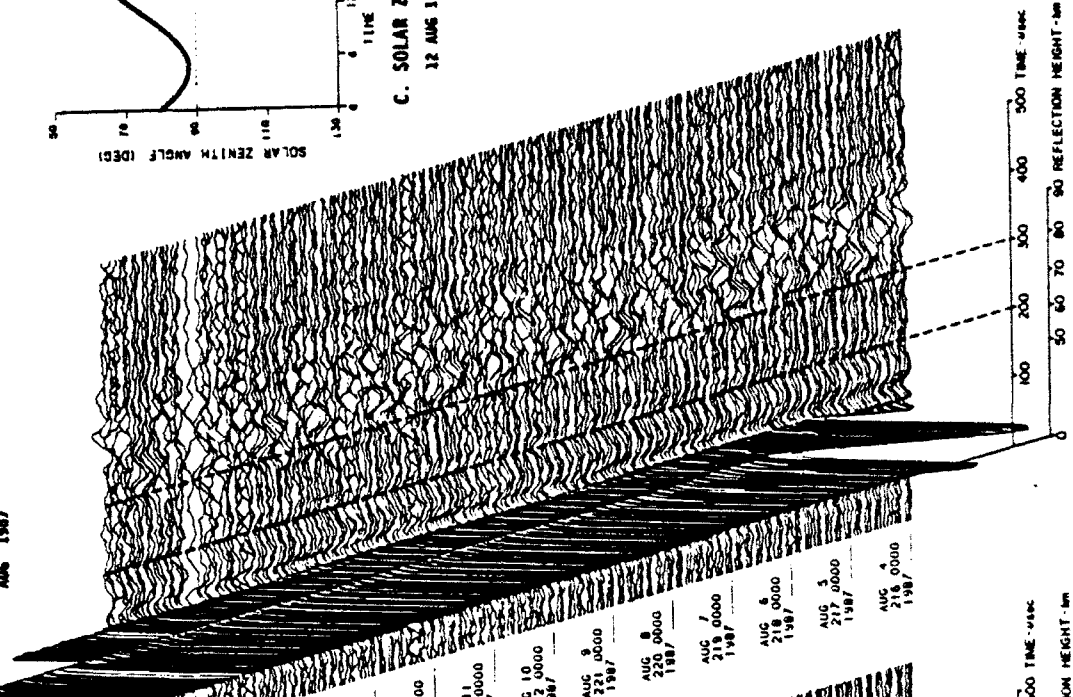


Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event

# RECEIVED PERPENDICULAR WAVEFORMS

E. NORMAL CONDITIONS  
AUG 1987

D. DISTURBED CONDITIONS  
AUG 1989

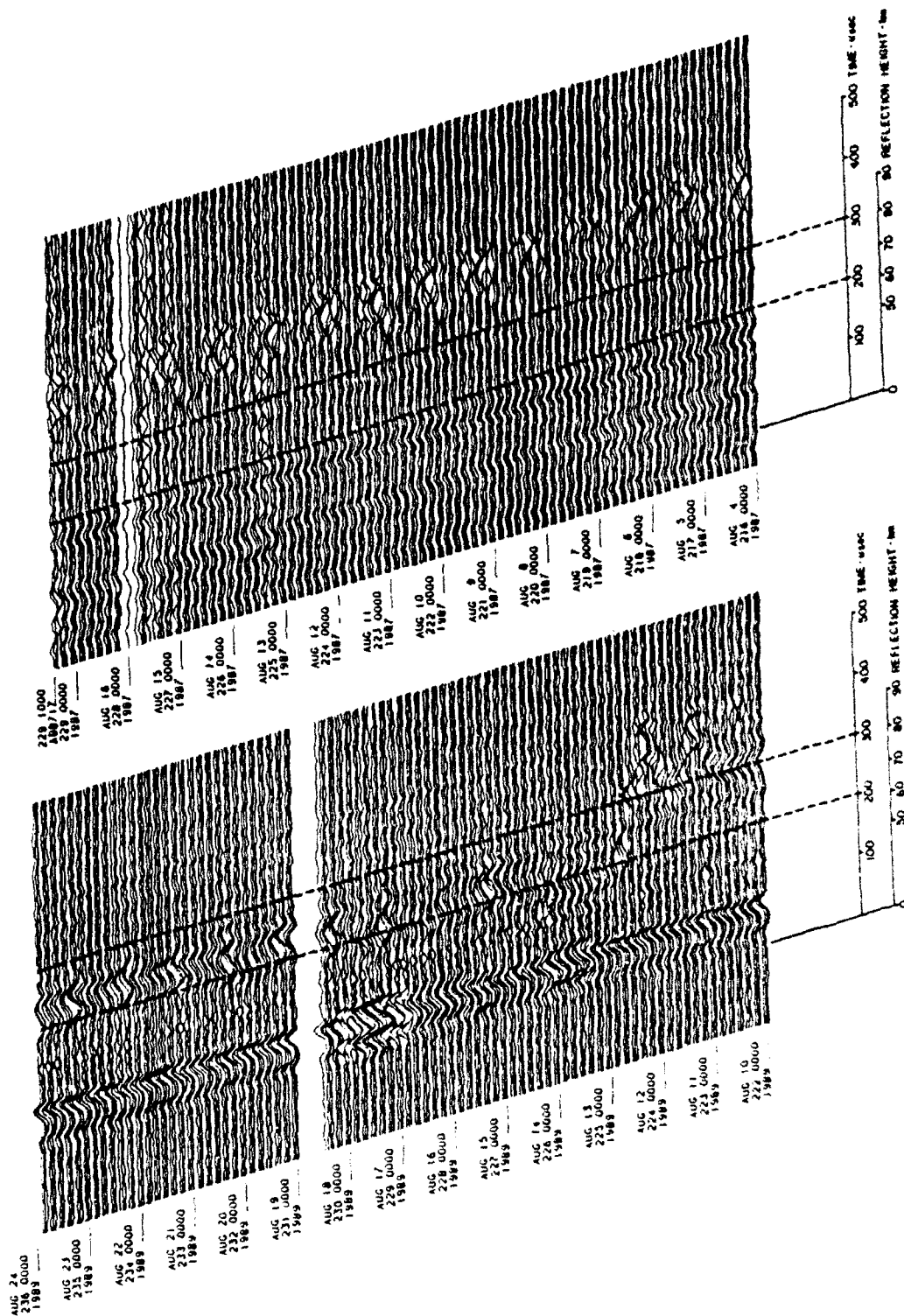
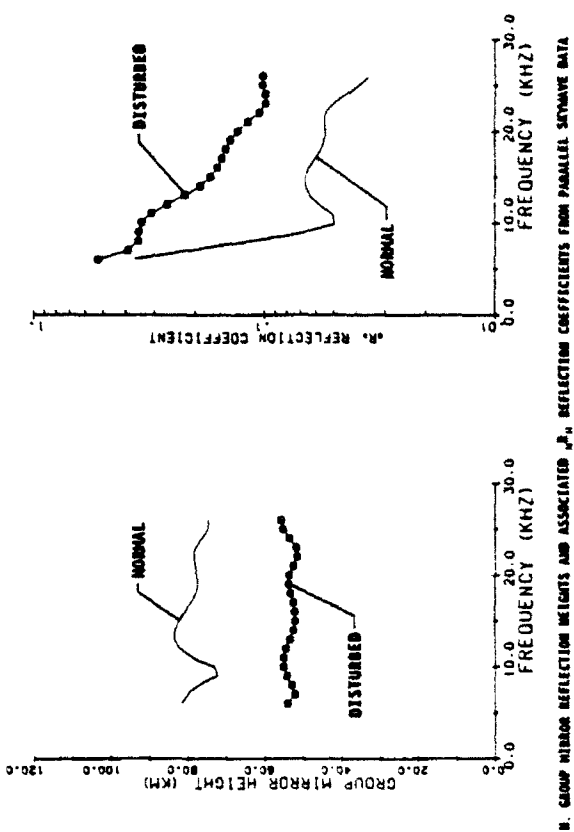
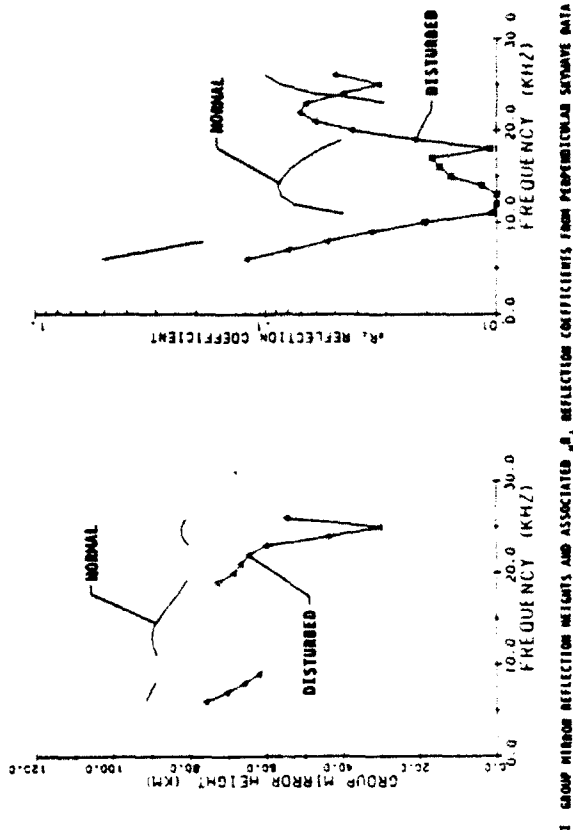


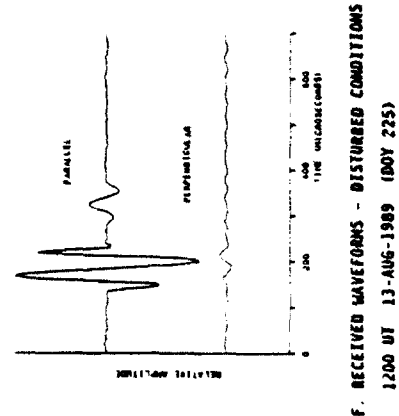
Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)



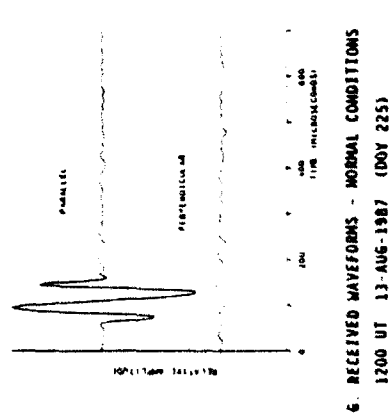
H. GROUP MIRROR REFLECTION HEIGHTS AND ASSOCIATED  $R_p$  REFLECTION COEFFICIENTS FROM PARALLEL WAVE DATA



I. GROUP MIRROR REFLECTION HEIGHTS AND ASSOCIATED  $R_p$  REFLECTION COEFFICIENTS FROM PERPENDICULAR WAVE DATA

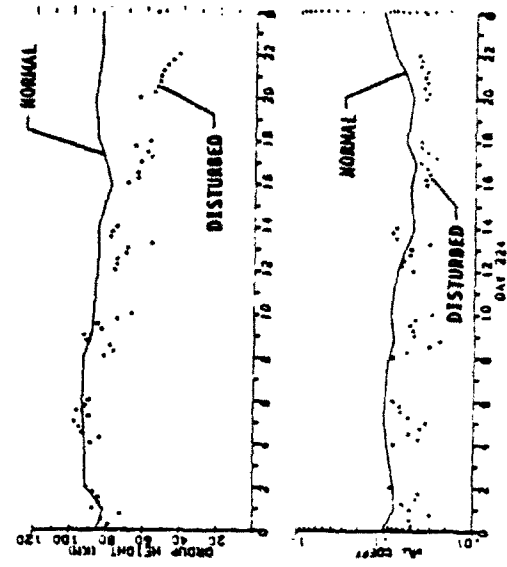
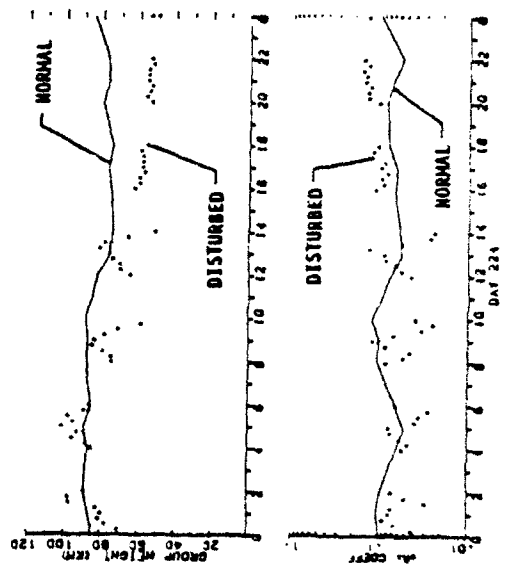
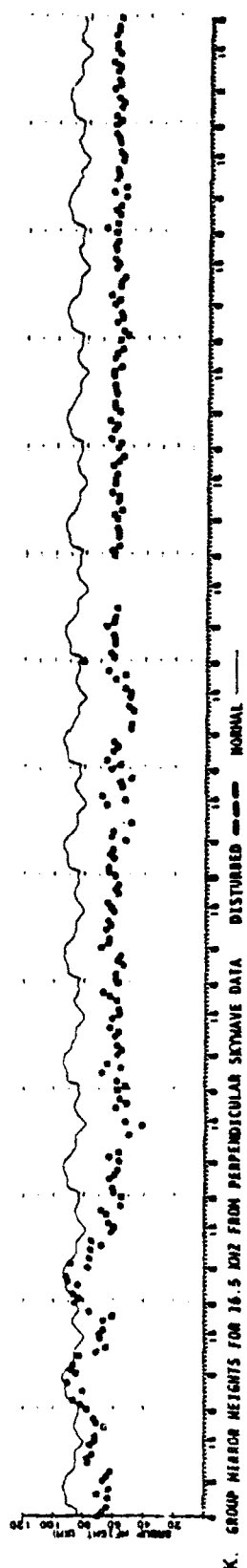
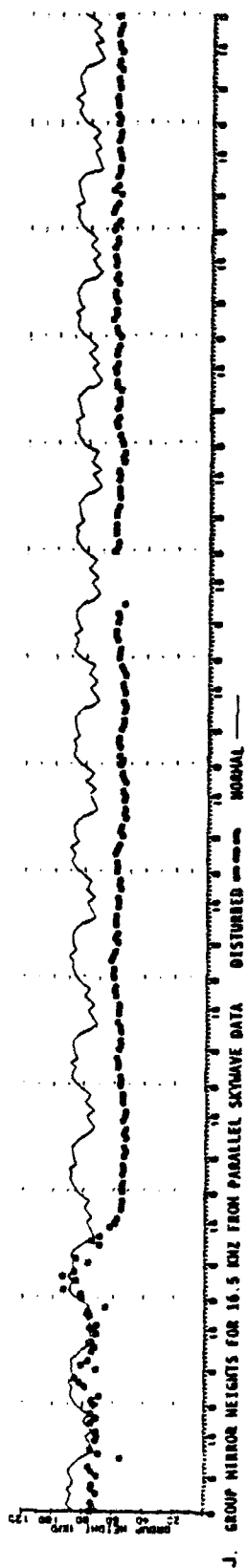


F. RECEIVED WAVEFORMS - DISTURBED CONDITIONS  
1200 UT 13-AUG-1989 (DOY 225)



G. RECEIVED WAVEFORMS - NORMAL CONDITIONS  
1200 UT 13-AUG-1987 (DOY 225)

Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)



L. Parallel 16.0 kHz Reflectivity Data  
15 Min Average for Day of Event Onset

M. Perpendicular 16.0 kHz Reflectivity Data  
15 Min Average for Day of Event Onset

Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)

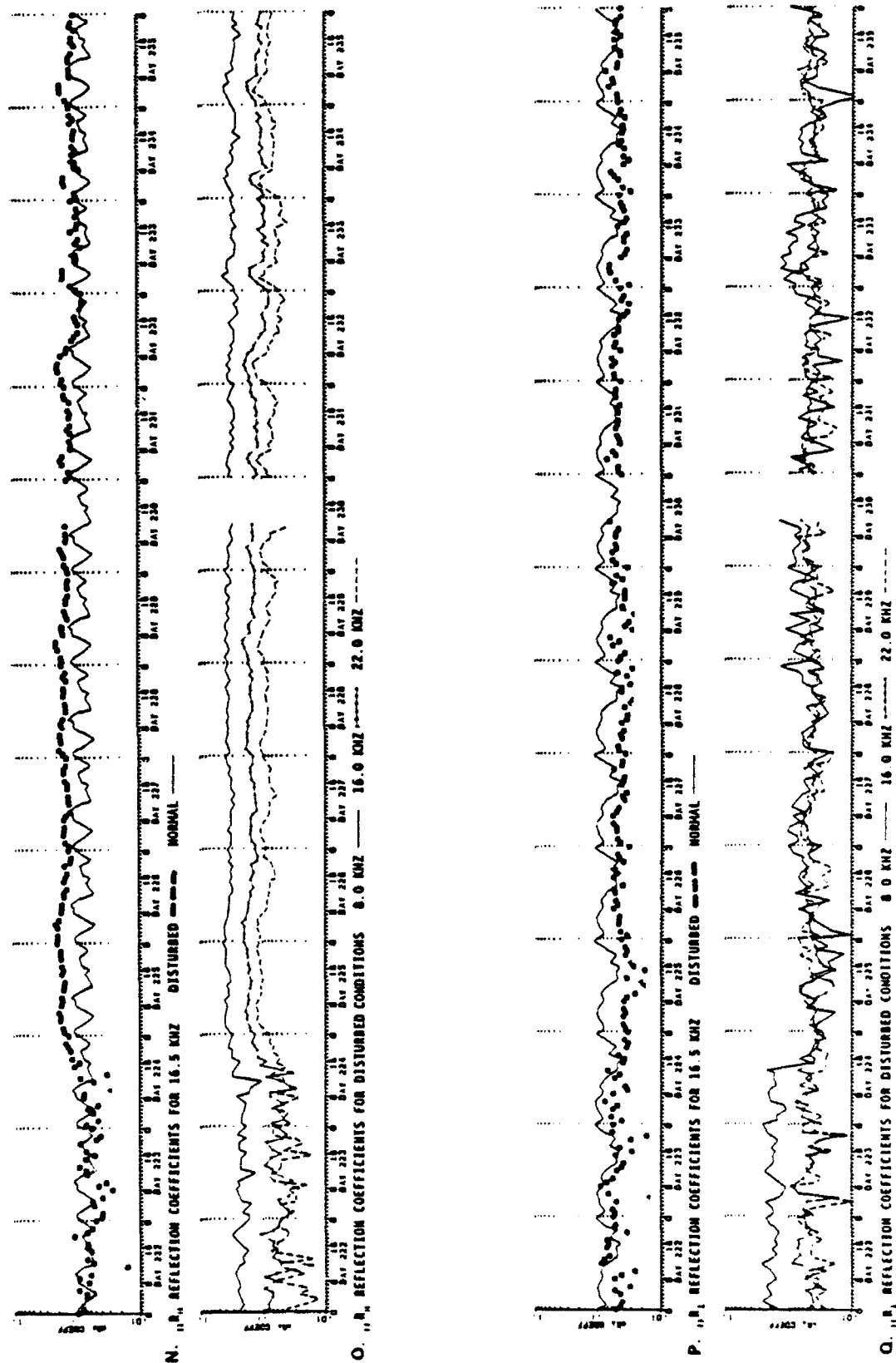
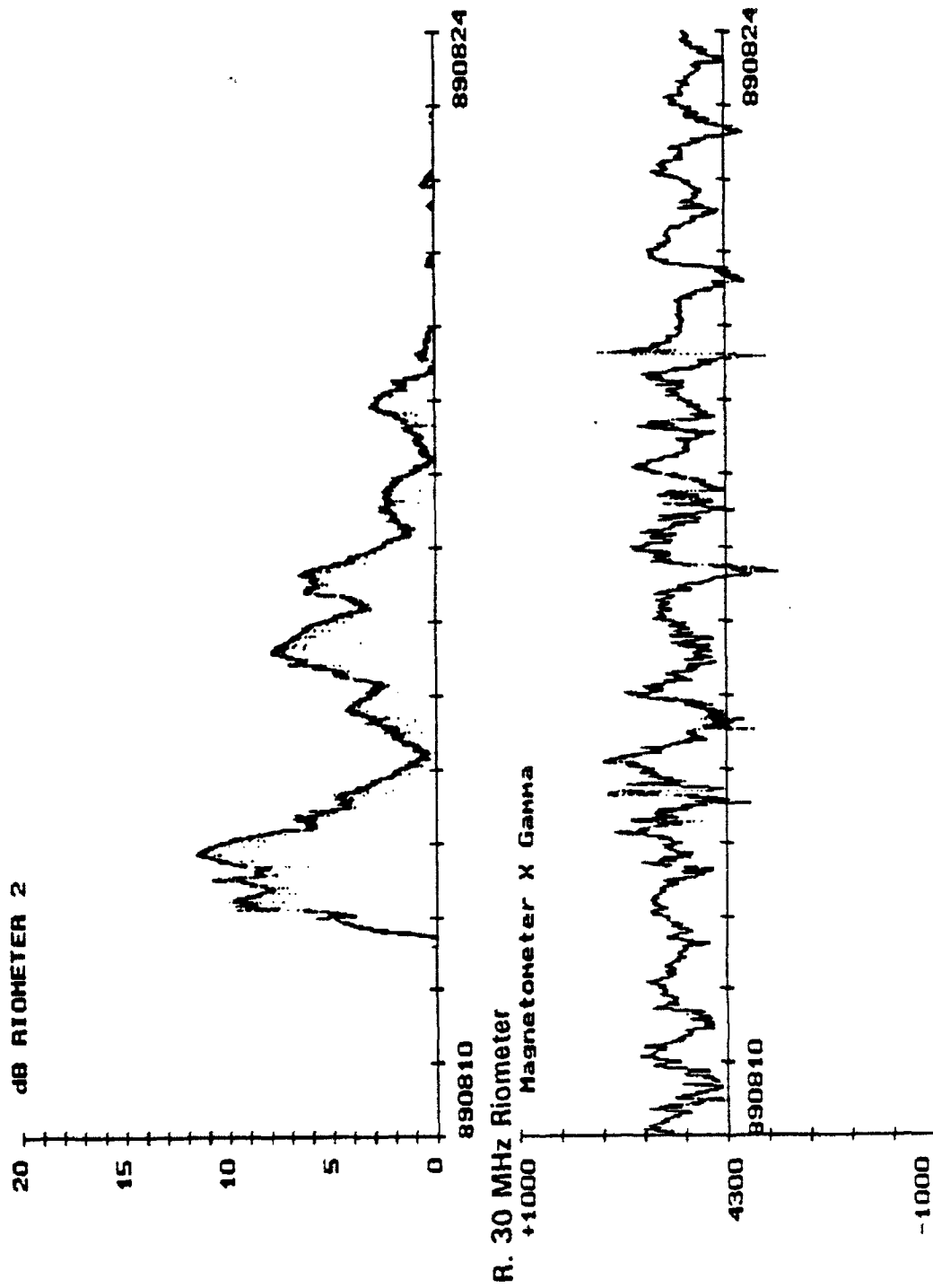
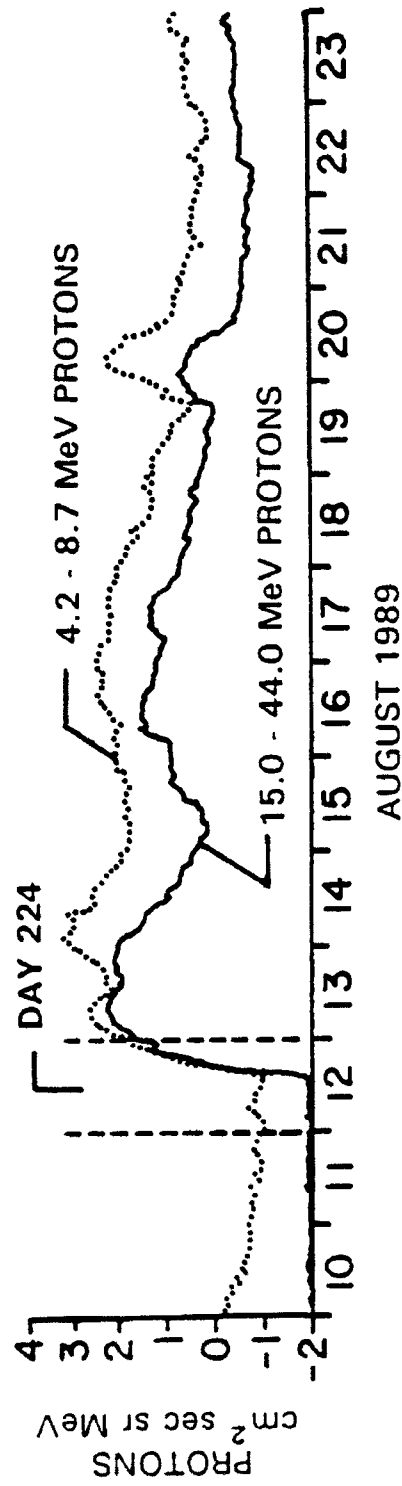


Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)



### S. X Component of Magnetic Field

Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)



T. GOES-7 Solar Proton Data

Figure 7. VLF/LF Ionospheric Reflectivity Data for August 1989 (DAY 224) Solar Particle Event (cont)



## 29 September 1989 (DAY 272) Solar Proton Event

DAY:	272 (29 September 1989)
Report Figure:	9
Related Solar Flare:	1047 UT 29 Sep 1989
	X-ray class: X9.8
Start of Ionospheric Disturbance:	1200 UT 29 Sep 1989
Time of Maximum 15.0-44.0 MeV Proton Flux:	0730 UT 30 Sep 1989
Maximum Flux:	200 particles/cm sec sr MeV
Length of Particle Event:	5 days
Lowest 16 KHz Reflection Height:	51 km
30 MHz Riometer Absorption:	10 dB
Solar Zenith Angle Range:	79deg - 106deg
Illumination Conditions:	Day - Night

A relatively strong, shorter than 12 August, event occurring during the transition from daylight to nighttime conditions. This disturbance dropped the effective reflection height at 16 kHz from 80 km at 1600 UT on 28 Sep (DAY 271) to a low of 51 km at 1600 on day 272. The event tapered off during the next 5 days and the ionosphere was essentially back to normal conditions by 4 Oct (DAY 277). A weaker event occurred on 5 Oct (DAY 278) with a duration of less than 2 days before returning to normal.

# RECEIVED PARALLEL WAVEFORMS

## A. DISTURBED CONDITIONS SEP-OCT 1989

## B. NORMAL CONDITIONS SEP-OCT 1987

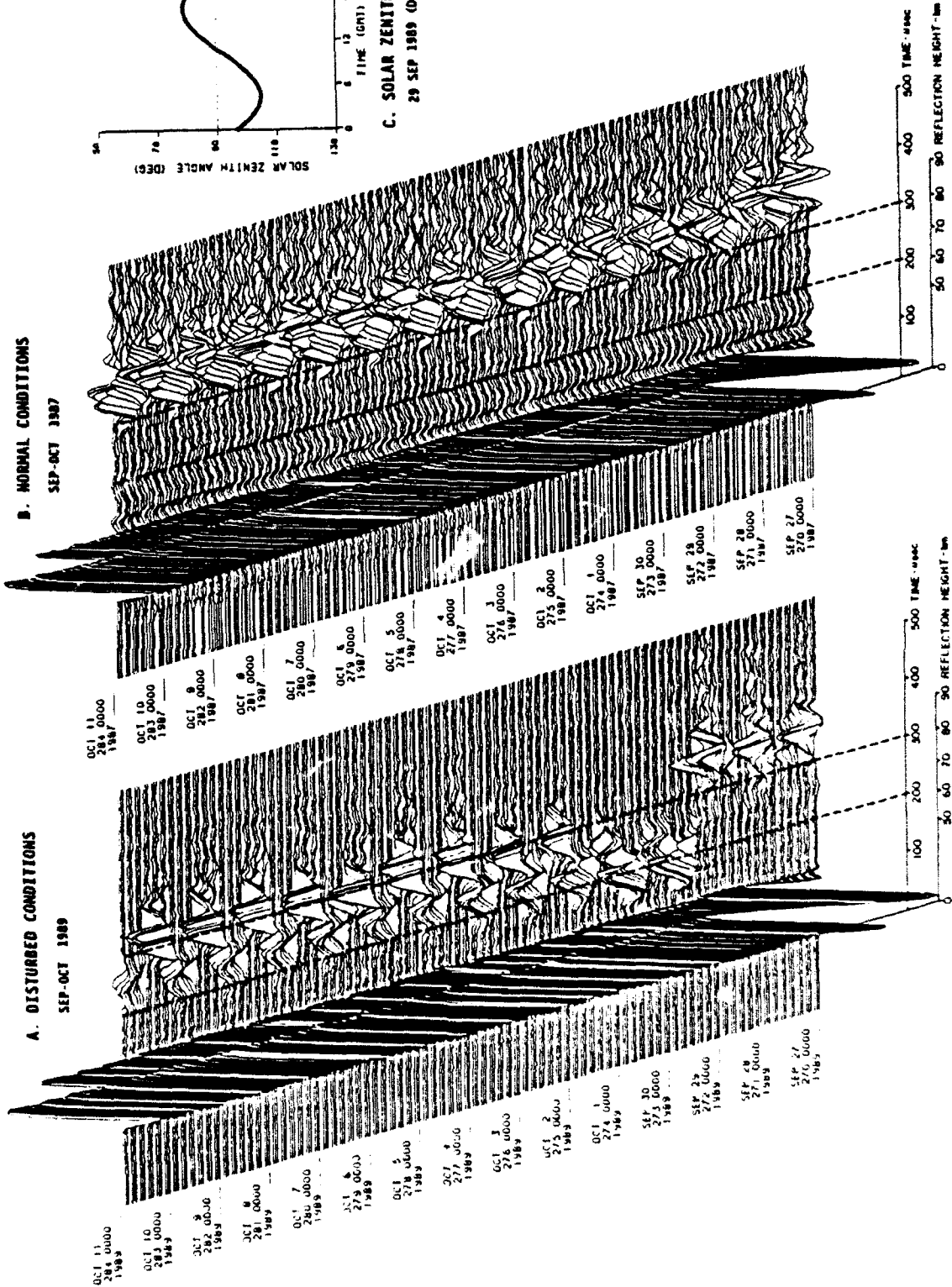
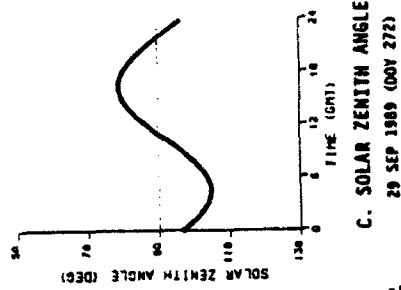


Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event

# RECEIVED PERPENDICULAR WAVEFORMS

E. NORMAL CONDITIONS

SEP-OCT 1987

D. DISTURBED CONDITIONS

SEP-OCT 1989

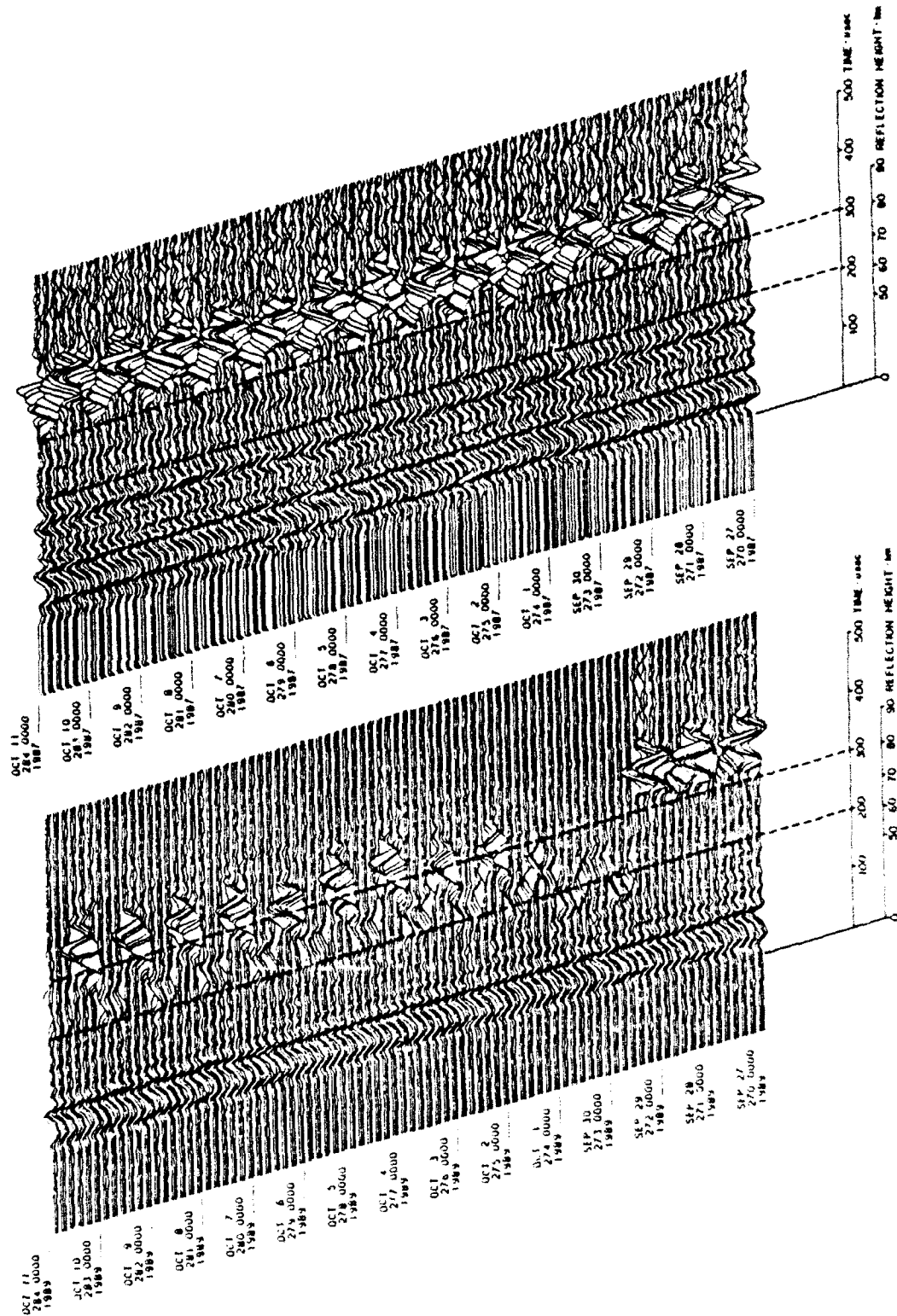


Figure 8. VLF/UF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)

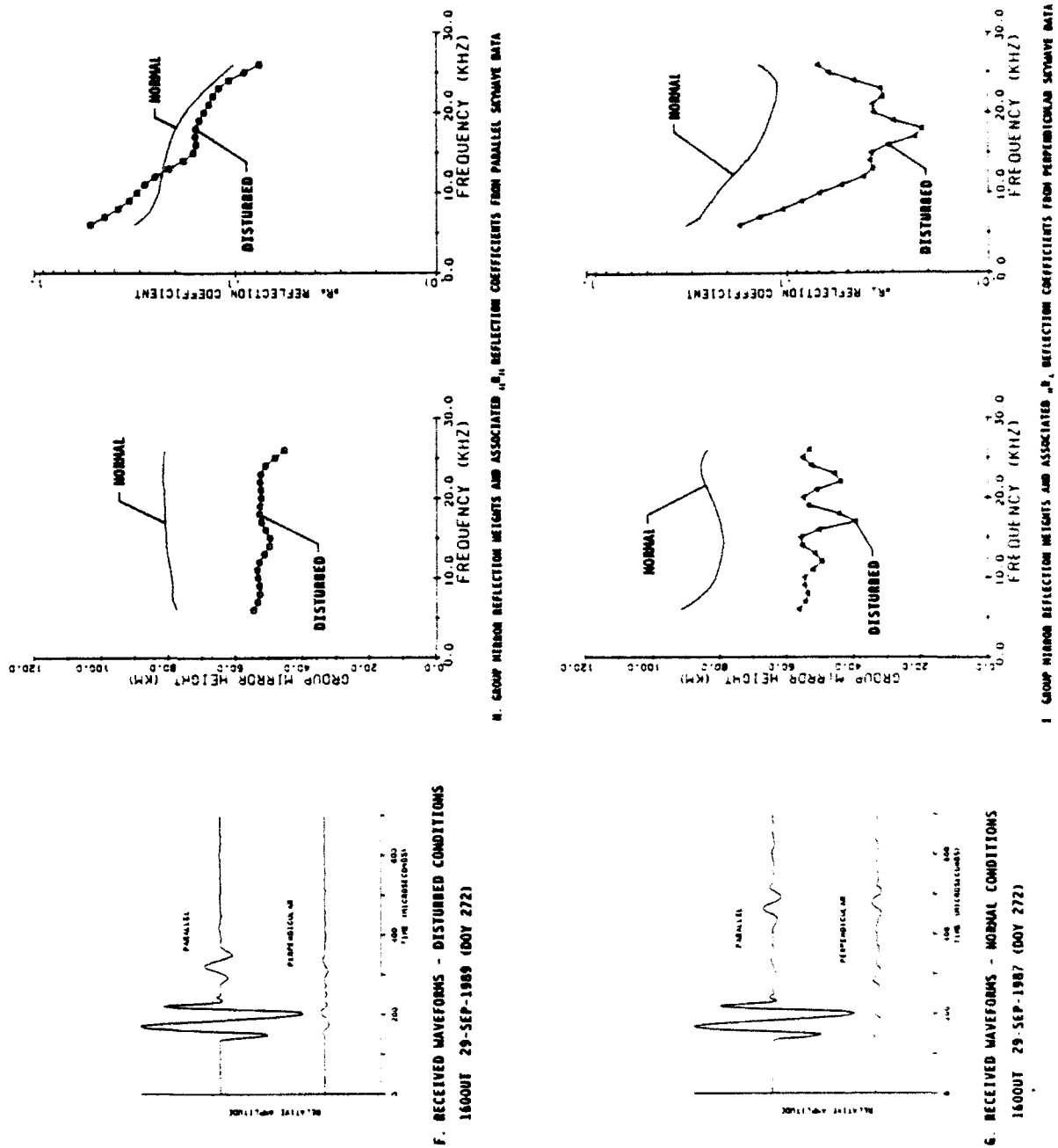
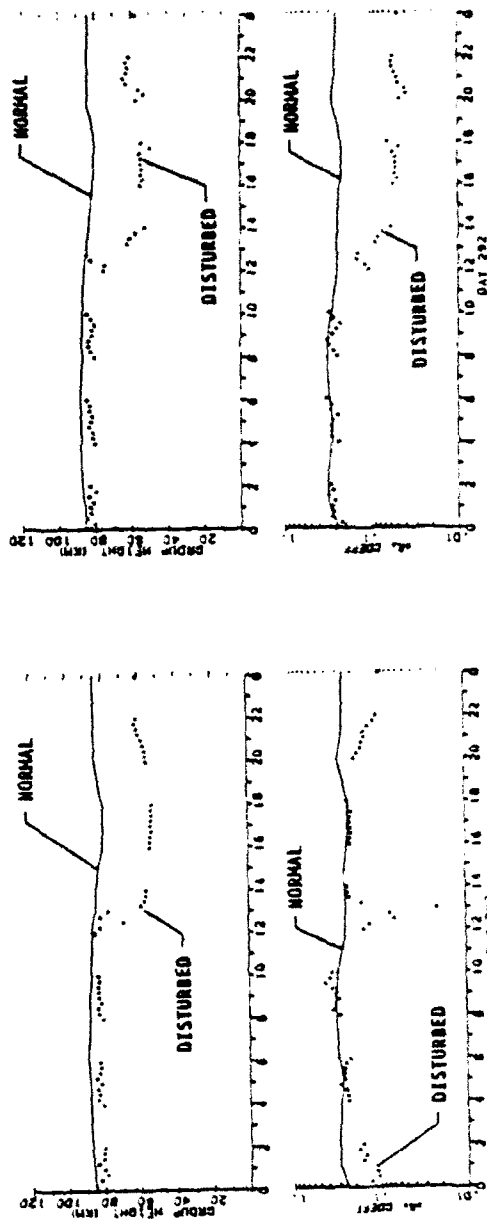
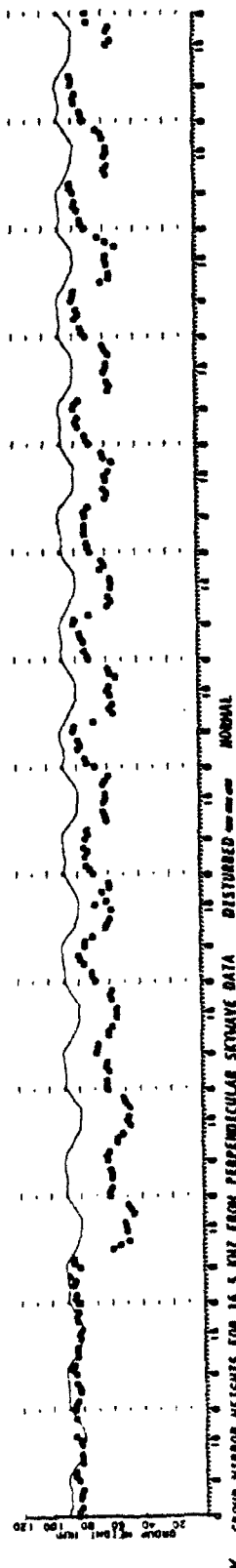
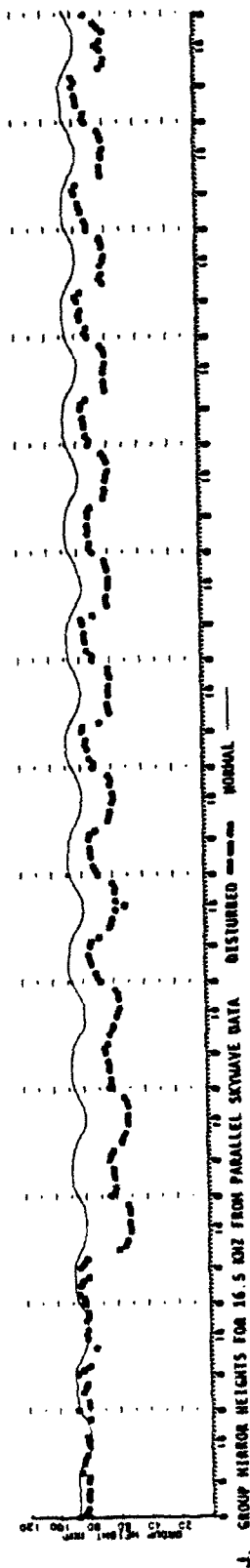


Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)



J. GROUP MIRROR HEIGHTS FOR 16.5 KHZ FROM PARALLEL SKYWAY DATA  
 K. GROUP MIRROR HEIGHTS FOR 16.5 KHZ FROM PERPENDICULAR SKYWAY DATA  
 L. Parallel 16.0 kHz Reflectivity Data  
 M. Perpendicular 16.0 kHz Reflectivity Data  
 15 Min Average for Day of Event Onset  
 15 Min Average for Day of Event Onset  
 Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)

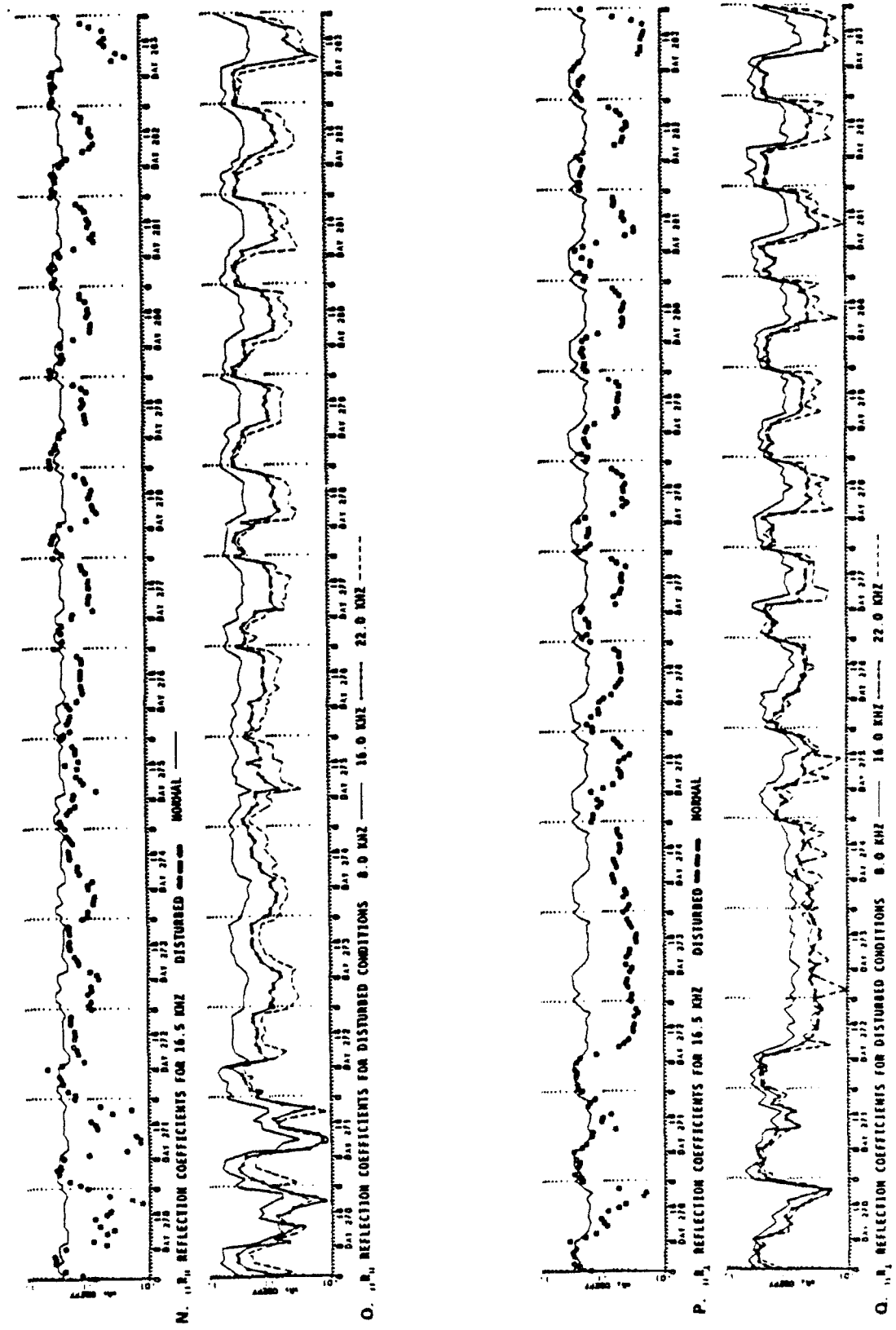
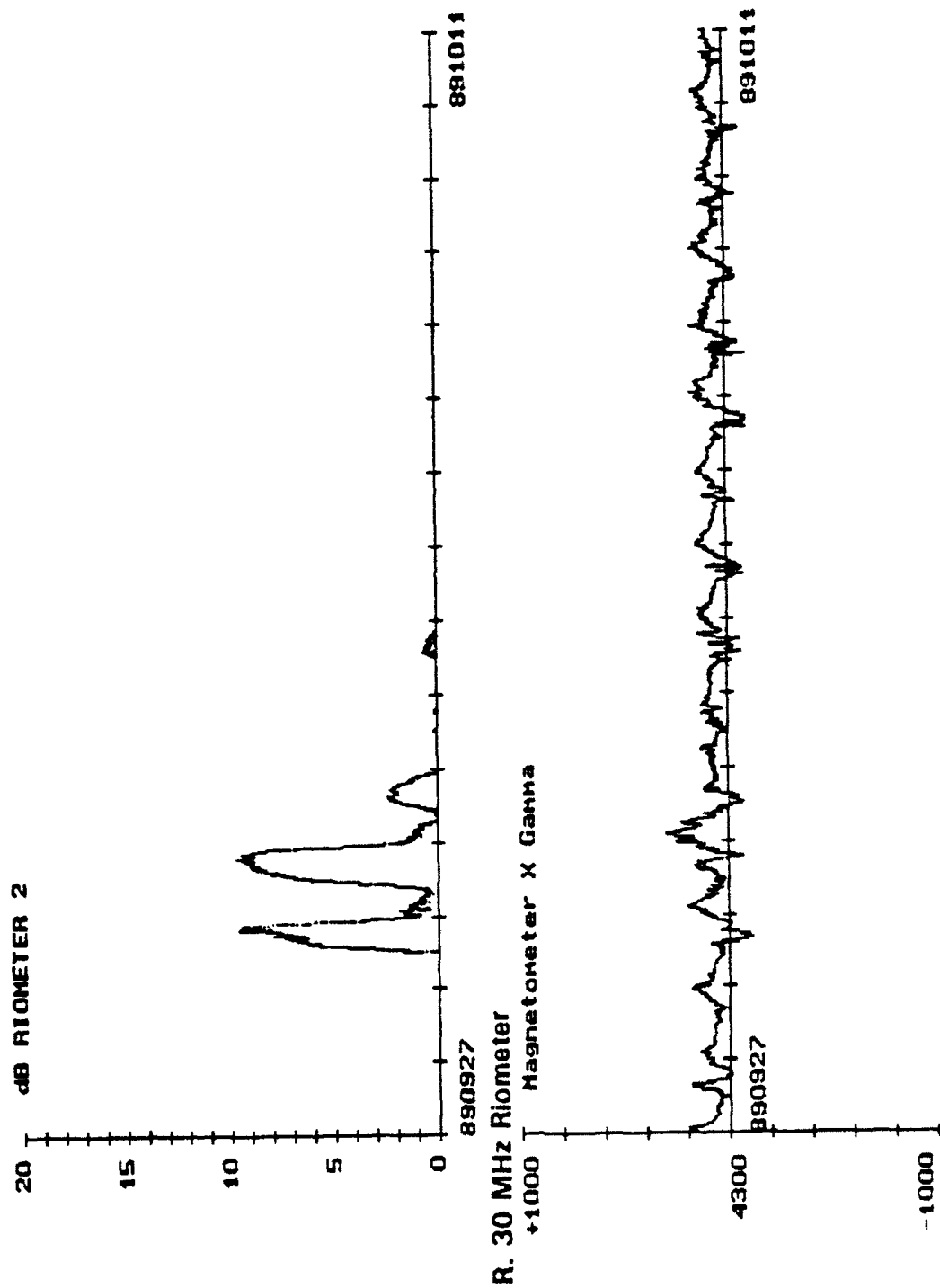


Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)



S. X Component of Magnetic Field

Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)

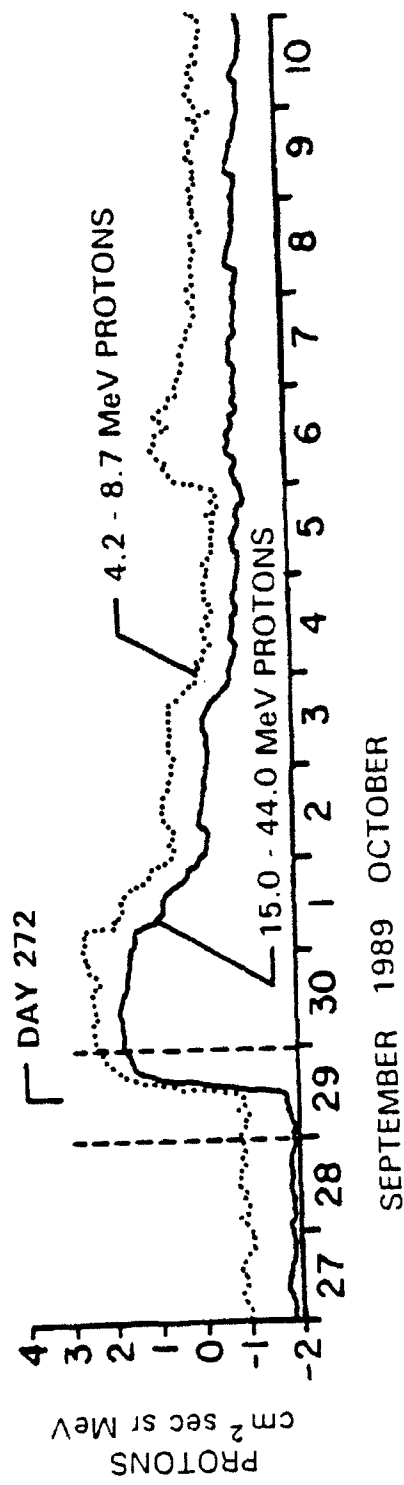


Figure 8. VLF/LF Ionospheric Reflectivity Data for September 1989 (DAY 272) Solar Particle Event (cont)



## 19 October 1989 (DAY 292) Solar Proton Event

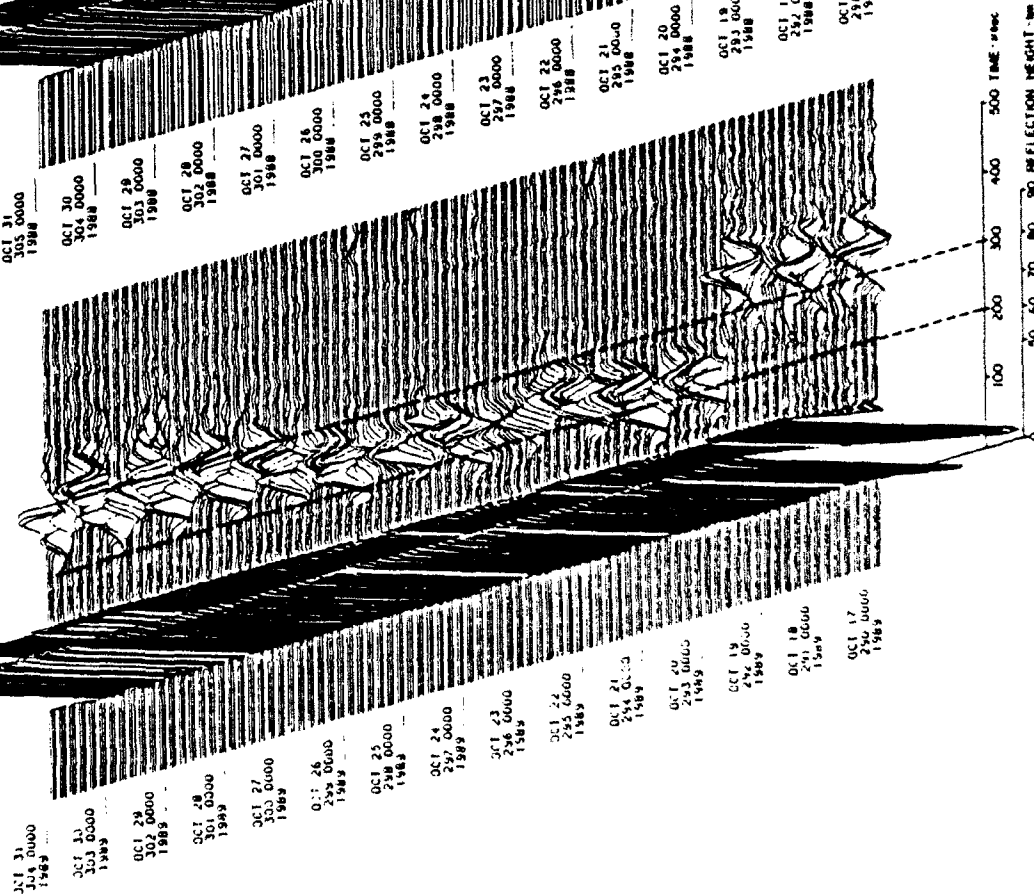
DAY:	292 (19 October 1989)
Report Figure:	9
Related Solar Flare:	1220 UT 19 Oct 1989 X-ray class: X13.0
Start of Ionospheric Disturbance:	1300 UT 19 Oct 1989
Time of Maximum 15.0-44.0 MeV Proton Flux:	1700 UT 20 Oct 1989
Maximum Flux:	900 particles/cm sec sr MeV
Length of Particle Event:	8 days
Lowest 16 KHz Reflection Height:	50 km
30 MHz Riometer Absorption:	> 15 dB
Solar Zenith Angle Range:	86deg - 113deg
Illumination Conditions:	Day - Night

This was the strongest event to occur during the year 1989. The drop in apparent parallel reflection height was from 80 km on 18 Oct (DAY 291) to a low of 50 km at 1700 on 20 Oct (DAY 293). The perpendicular reflection height during this period dropped from 81 km to a low of 47 km. During the peak on 20 Oct of this event the readings on the riometer were saturated at greater than 15 dB absorption. These heights were the lowest we recorded during our measurement series, the previous lowest parallel heights were 51 km during the events of Sep 1978 and Sep 1989.

# RECEIVED PARALLEL WAVEFORMS

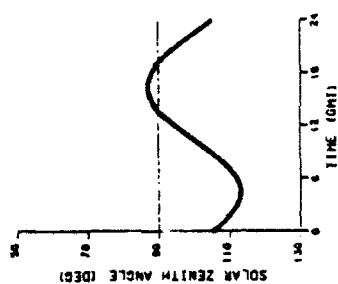
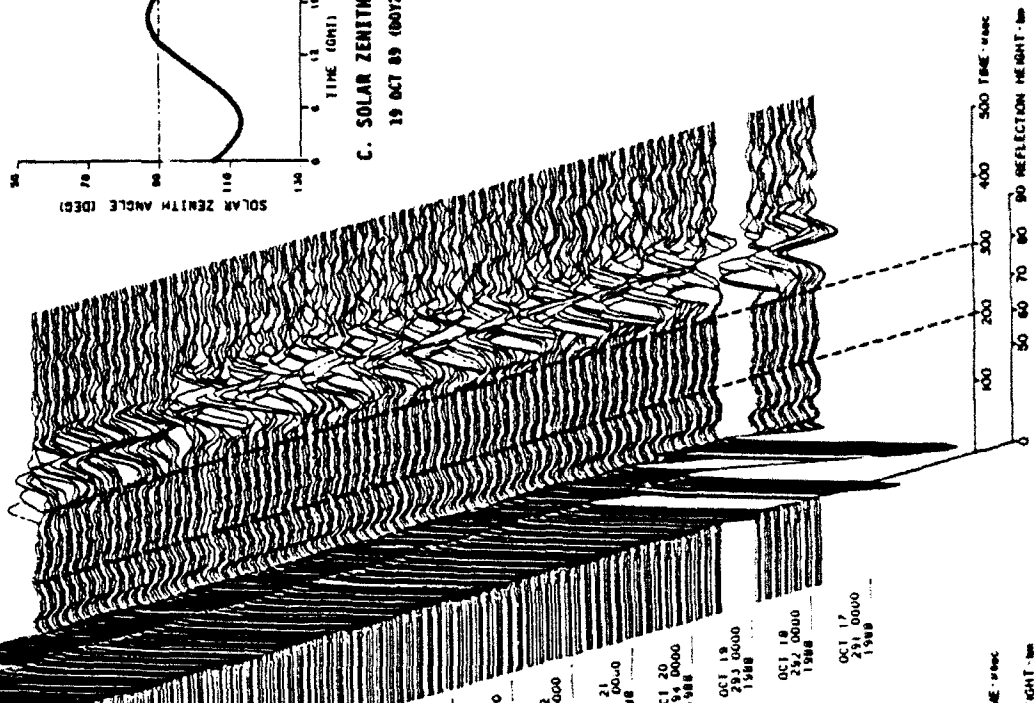
## A. DISTURBED CONDITIONS

OCT 1989



## B. NORMAL CONDITIONS

OCT 1988



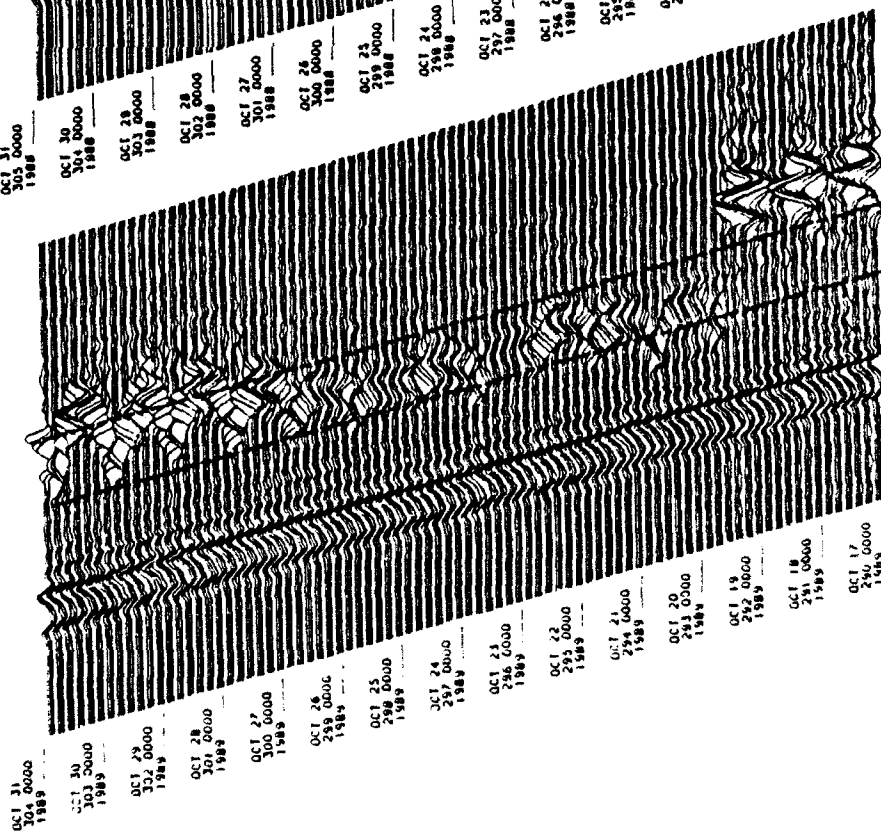
C. SOLAR ZENITH ANGLE  
19 OCT 89 (001232)

Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event

# RECEIVED PERPENDICULAR WAVEFORMS

## D. DISTURBED CONDITIONS

OCT 1989



## E. NORMAL CONDITIONS

OCT 1988

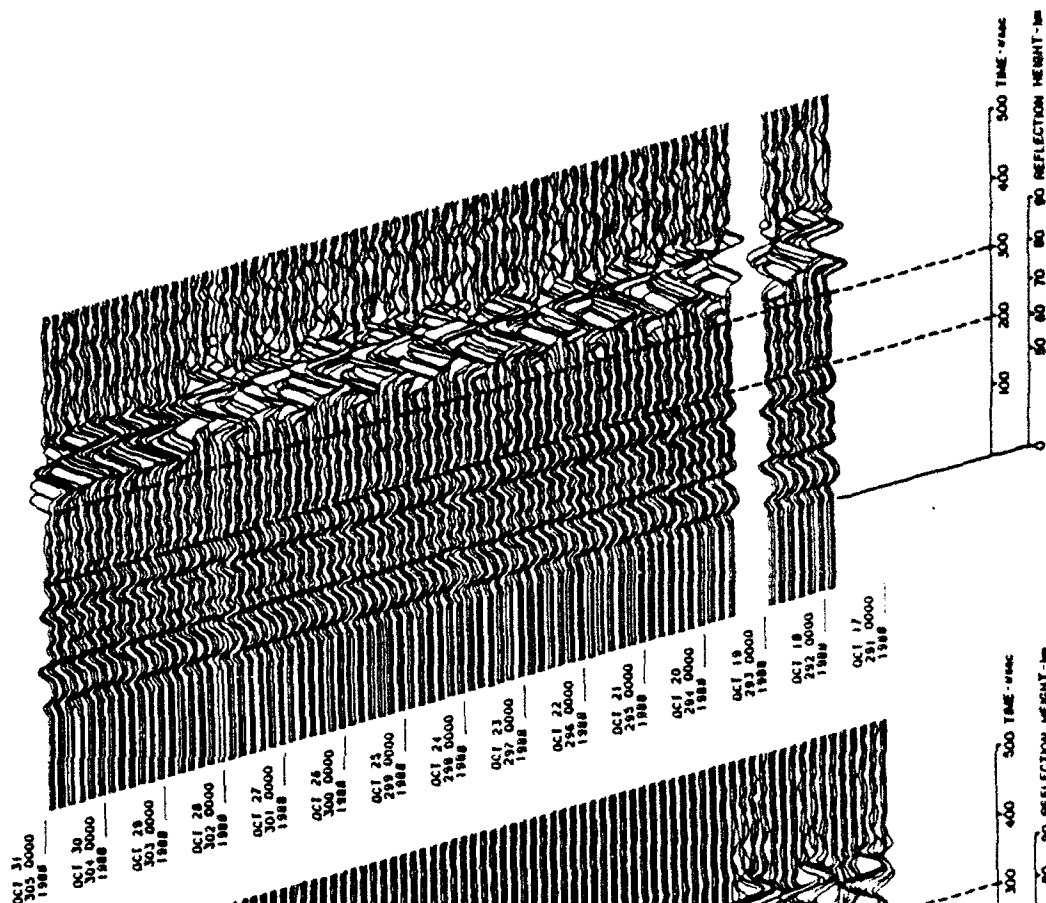


Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)

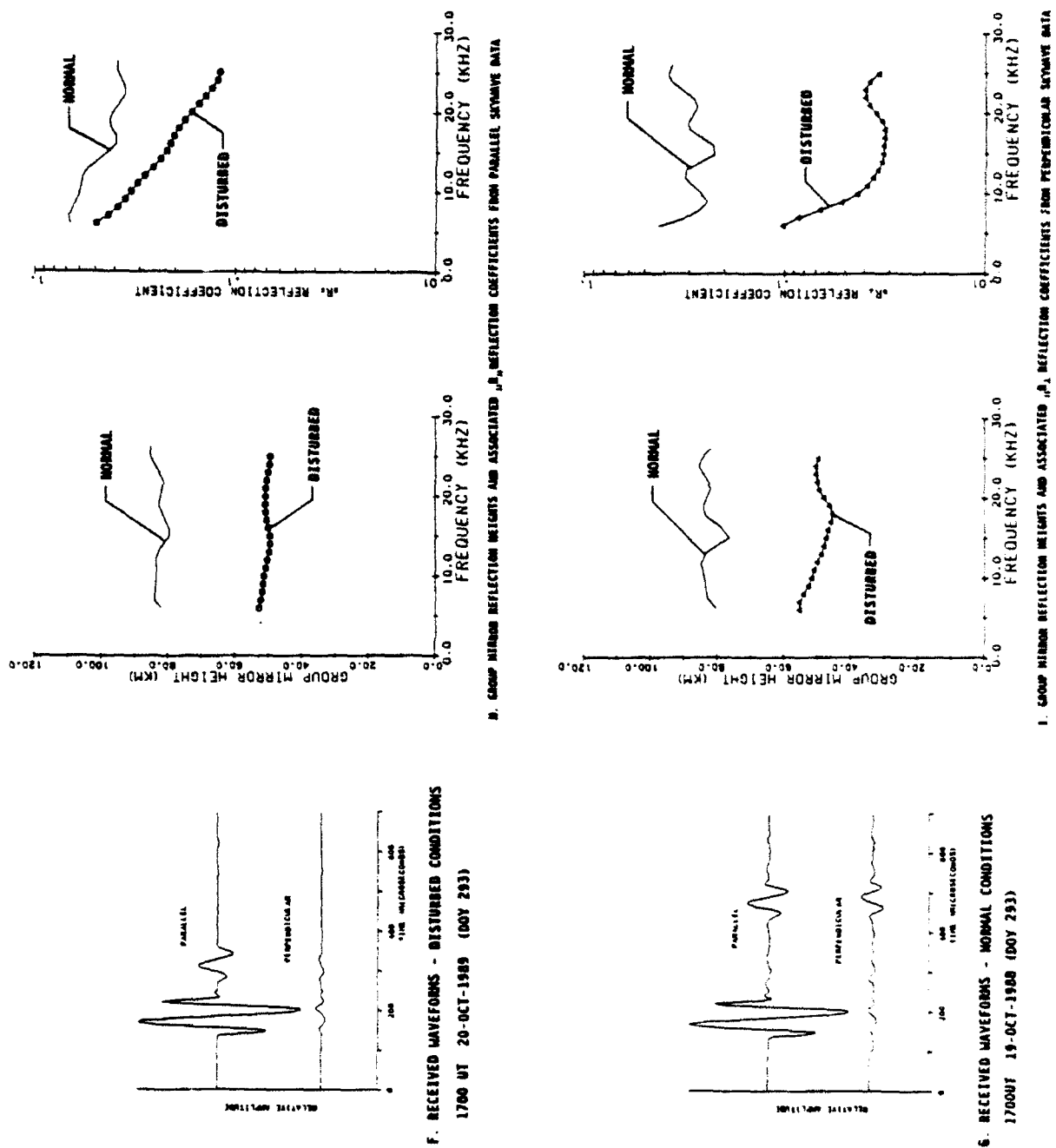
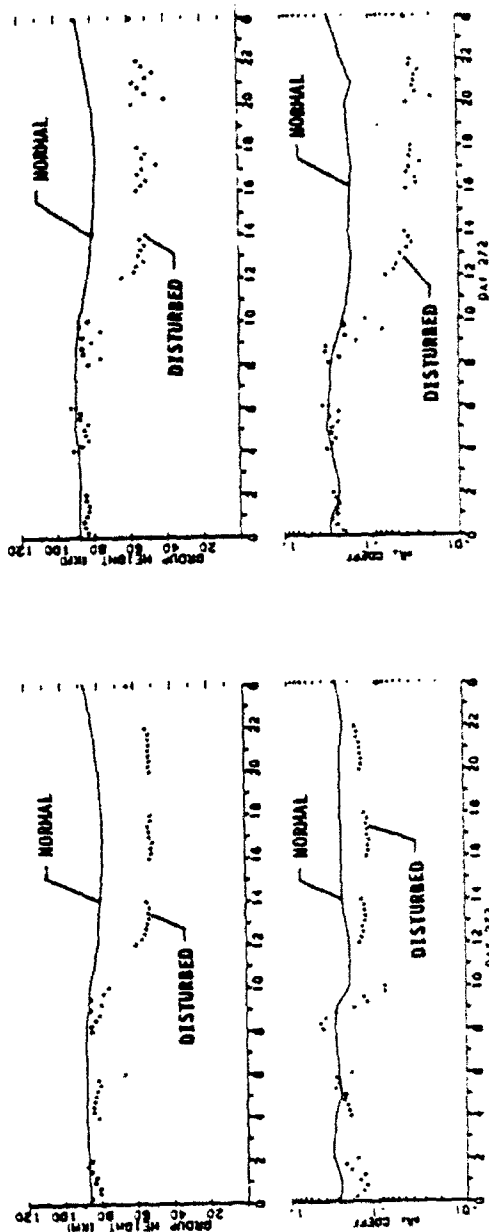
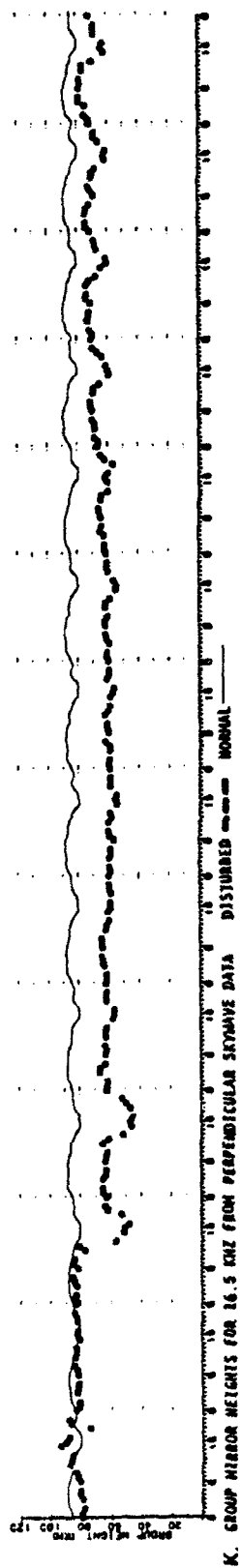
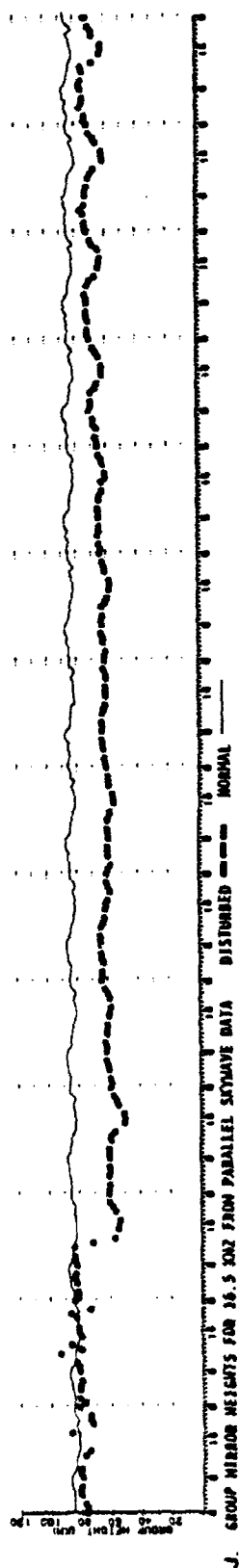


Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)



L. Parallel 16.0 kHz Reflectivity Data  
15 Min Average for Day of Event Onset  
M. Perpendicular 16.0 kHz Reflectivity Data  
15 Min Average for Day of Event Onset

Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)

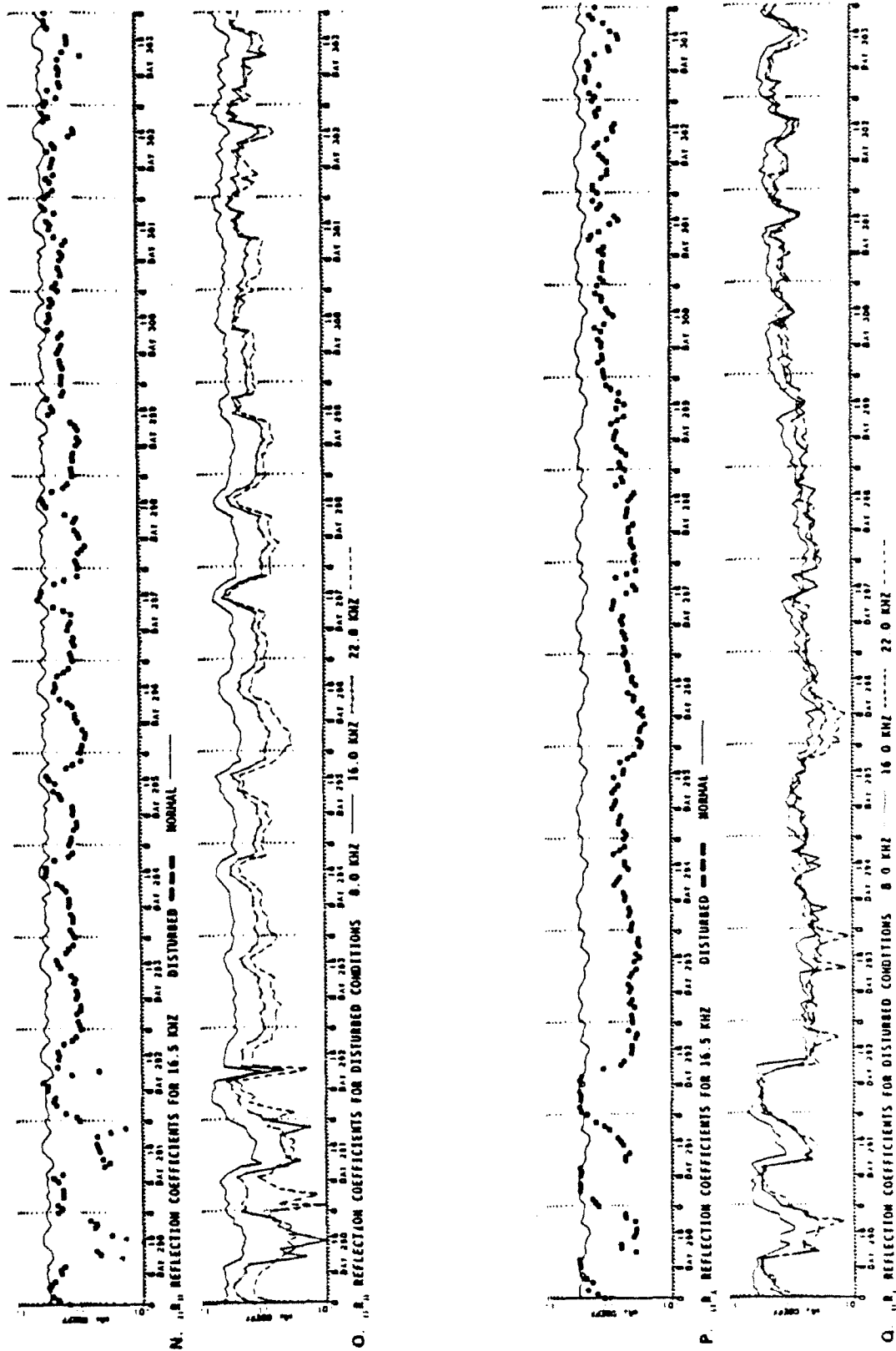
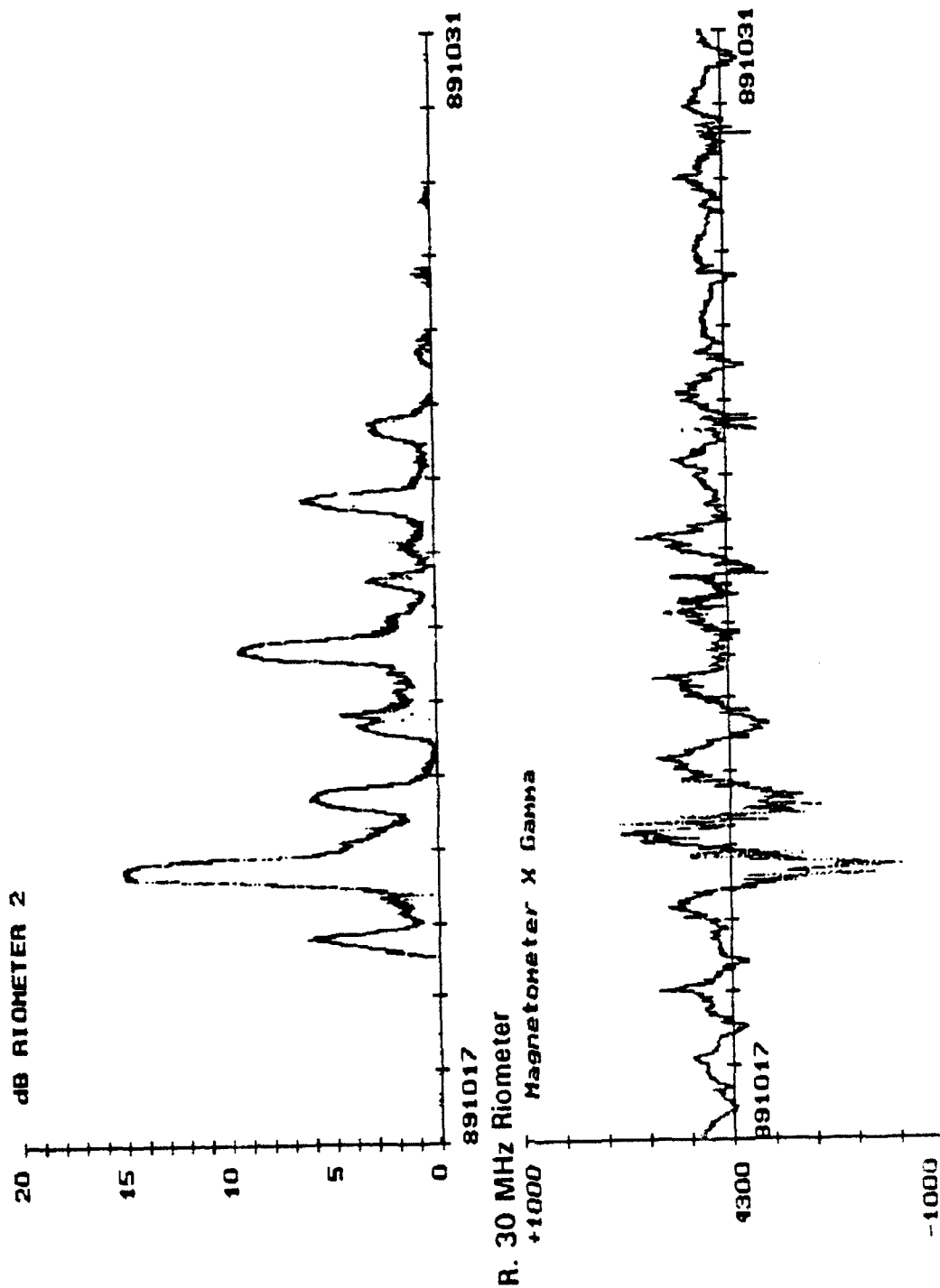
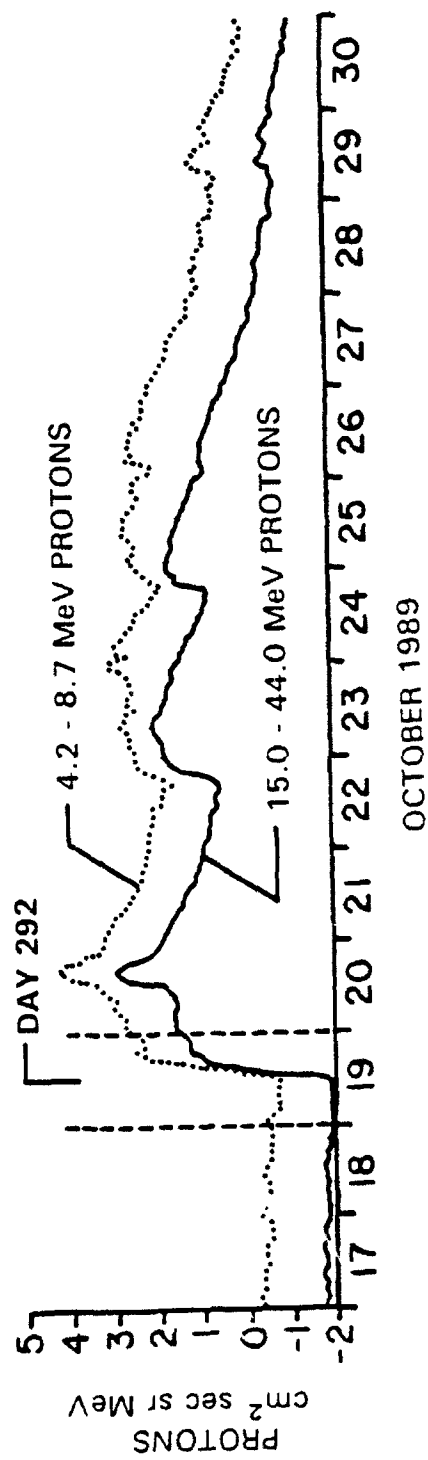


Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)



### S. X Component of Magnetic Field

Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)



T. GOES-7 Solar Proton Data

Figure 9. VLF/LF Ionospheric Reflectivity Data for October 1989 (DAY 292) Solar Particle Event (cont)





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